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PREFACE

This report was prepared for the U.S. Geological Survey, Research and Development Programs for Outer Continental Shelf Oil and Gas Operations. It presents a review of the state of the art in the design and construction of offshore drilling facilities that may be used in oil/gas exploration on the northern Alaska Outer-Continental Shelf (OCS). It addresses the hazards posed by the Arctic environment, reviews potential development concepts and their vulnerabilities, and draws conclusions as to the risks.

Exploitation of petroleum reserves on the Arctic Outer Continental Shelf will require the development of new strategies in exploratory drilling and production, if such activity is to remain both safe and economically viable. A portion of this technology has already been developed as a result of experience on the Alaskan North Slope, in the Canadian Arctic Archipelago, and during the major activity in the Canadian Beaufort Sea. Limited exploratory drilling experience exists in the Alaskan Beaufort Sea. A formidable problem which remains, however, is the development of safe permanent structures for offshore production in ice-prone Arctic areas.

Since 1972, some initial experience has been gained with exploratory drilling in the shallow waters of the Canadian Beaufort Sea using earth-filled islands, in deeper waters of the Canadian Beaufort Sea using drillships, and with man-made ice platforms in the Canadian Arctic Islands. Also, some exploratory drilling was done in the shallow waters off the north coast of Alaska. More recently, drilling was conducted off the coast of Greenland using conventional drillships during the summer months when icebergs were present. However, fixed production platforms have been utilized only in Cook Inlet, Alaska, where the ice problem is much more limited than in the offshore Arctic.

A number of new concepts have been proposed, or are being developed to deal with emplacement of structures in ice-prone areas. These include caisson reinforced islands, multi-season ice islands,* and monopod structures with cones and other ice-breaking features. A few of these approaches have been tested under field and laboratory conditions. The other concepts are described and evaluated in relation to the known environmental forces they must survive.

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*Man-made grounded ice platforms are called ice islands in this report.

In general, this study was limited to exploration and production structures fixed to the ocean floor or ice. Drill-ships were excluded from the study since the near-term lease sale of tracts will be in waters too shallow for operations. The specific elements of the structures reviewed were the foundation, support members, operating deck structure, gathering lines, pipelines, risers, wellhead, temporary oil/gas storage, blowout prevention, logistics support provisions and general plans of operations. Emphasis was placed on those elements of offshore structures that fall under the regulatory responsibility of the U.S. Geological Survey.

I. ARCTIC ENVIRONMENT

A. REGIONAL SETTING

1. Coastal Physiography

The offshore portion of the Alaskan Arctic encompasses two major bodies of water, the Beaufort and Chukchi Seas. The Chukchi Sea (Figure 1-1) begins at the Bering Strait (66° N. latitude) and continues northward about 500 km (300 mi) to Point Barrow (71° N. latitude). Because of its irregular margin, the Chukchi includes more than 1,100 km (700 mi) of the eastern Alaskan coast. The coastline is punctuated with numerous capes and headlands. Between these headland areas, there are gently-curving shallow embayments which are exposed to the open sea. A few areas along the coast contain strings of barrier islands backed by sheltered lagoons.

South of Cape Lisburne there is a very large embayment between Point Hope and the Bering Sea. Generally known as the Hope Sea Basin, it is an area of considerable interest for future petroleum exploration. The easternmost part of the basin is a very shallow but large bay called Kotzebue Sound.

The land bordering the shores of the Chukchi Sea consists of flat coastal plains dotted with numerous lakes, ponds and small streams. There are some interspersed areas of low

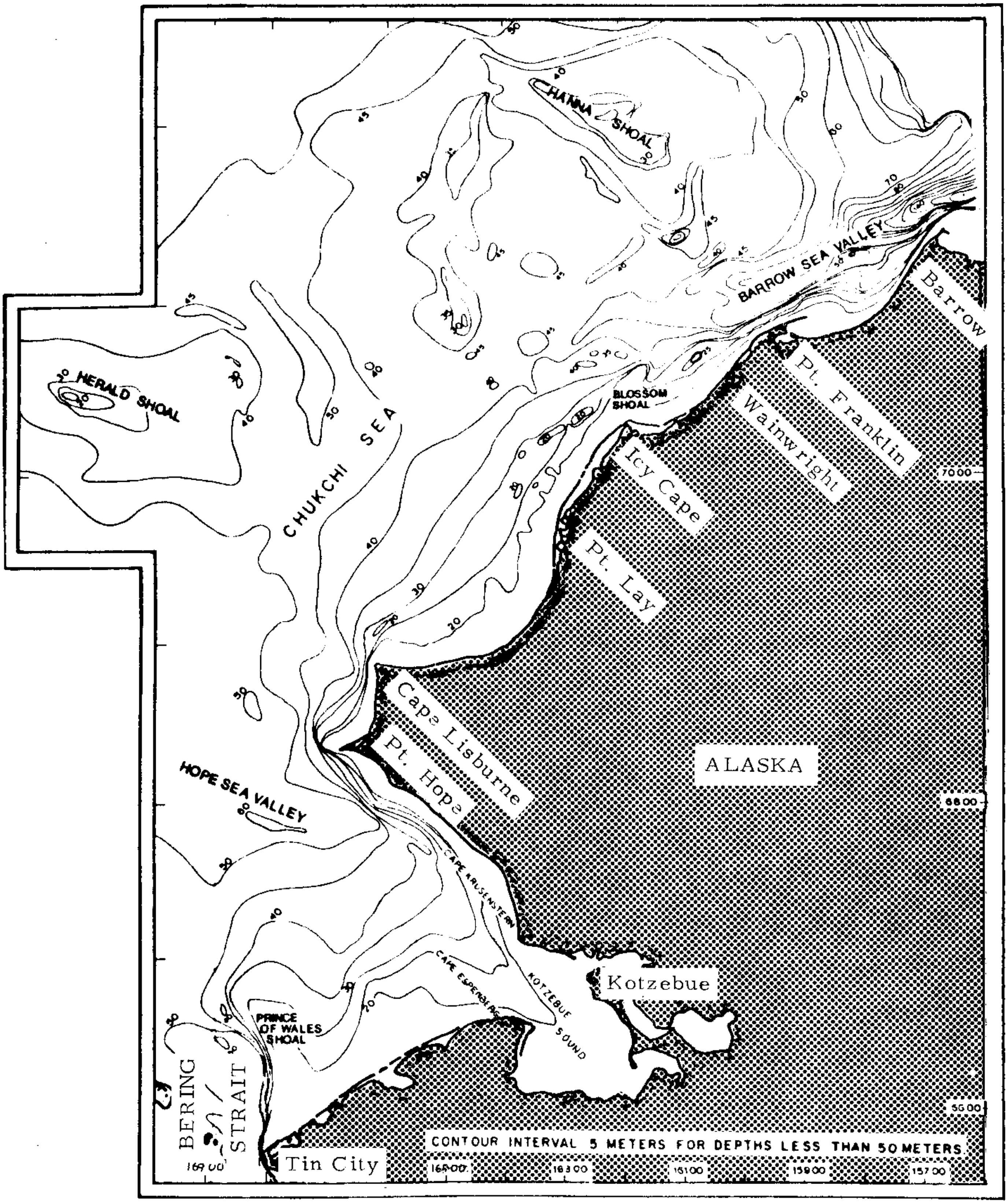


Figure 1-1. Chukchi Sea (Toimil, 1978)

rolling hills which rise to heights of a few hundred meters above the coastal plain. However, the dominant feature of the landscape is its flatness. Vegetation on the coastal plain is mainly tundra which serves to accentuate the area's barren appearance.

The Alaskan sector of the Beaufort Sea (Figure 1-2) extends from Demarcation Point (141° W longitude) to Point Barrow (153° 30' W. longitude), a distance of approximately 610 km (380 mi). The Beaufort Coast has many of the same coastal features as the Chukchi. However, a much greater proportion of the Beaufort coastline is bordered by barrier island chains which lie several miles offshore. These islands provide a great deal of protection to the mainland coast and many are backed by shallow lagoons. The most exposed part of the Beaufort coast is found in the western sector, especially at Smith and Harrison Bays where there are no offshore barrier islands.

One feature which is common along the Beaufort Coast, but which is largely absent on the Chukchi coast, is a complex of river delta systems. These deltas have been formed by river systems which originate in the Brooks Range and flow northward providing drainage for the Arctic Slope. Major river systems include the Mead, Ikpikpuk, Colville, Kuparuk, Sagavanirktok, Shaviovik, Staines, Canning, Hulahula, and Kongakut. During the winter months, the rivers cease to flow as a result of freezing. For several weeks in the late spring they thaw, and often flood the low-lying coastal areas.

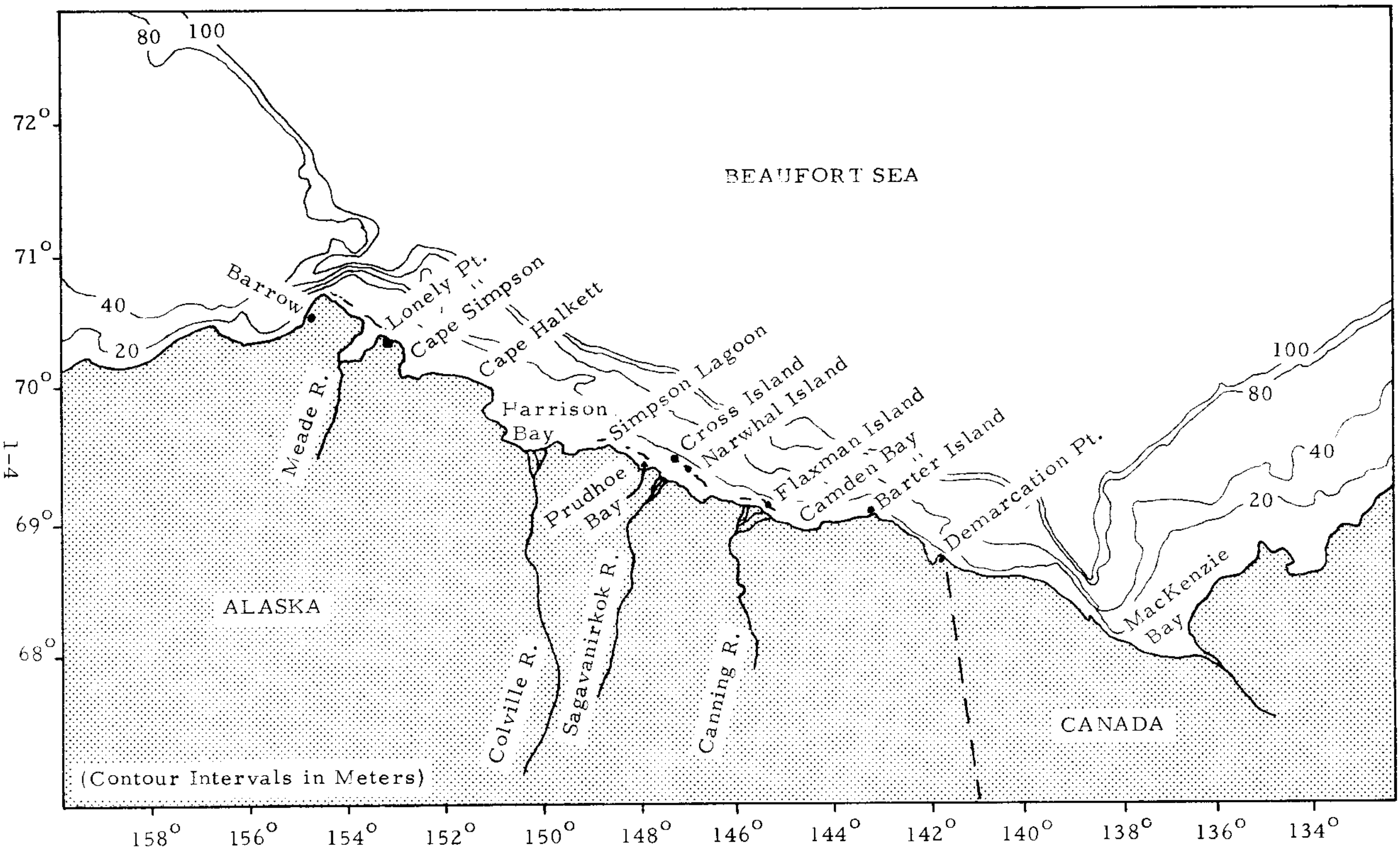


Figure 1-2. Beaufort Sea

Land along the coast consists of narrow beaches bordered by low but steep bluffs usually less than 3m (10 ft) in height. In many places these bluffs are actively retreating as a result of thermal and wave erosion during the summer open-water season. Behind the bluffs lies the low, flat Arctic coastal plain which varies in width from 18 km (11 mi) at the Canadian border to 180 km (110 mi) at Point Barrow. The plain is underlain by continuous permafrost with depths ranging to perhaps 600m (2000 ft). The most significant feature of the plain is a complex of thousands of small lakes and streams which cover an area of 435,000 sq. km (168,000 sq. mi).

2. Coastal Bathymetry

The continental shelf of the Chukchi Sea is a flat, almost featureless plain having average depths of 45-55m (145-180 ft). (Creager and McManus, 1967). The slope gradients on the shelf are extremely gentle. Maximum slopes reported are about 2 degrees but most are less than 2 minutes. The 20m (66 ft) depth contour lies an average of 16 km (10 mi) offshore except along the northeastern coast where relatively steep gradients are found in the vicinity of the Barrow Sea Valley. Adjacent to the exposed coast, the only significant bottom relief is caused by scour depressions produced by dragging chunks of sea ice and the keels of pressure ridges. Kotzebue Sound, in the southeastern Chukchi, is very shallow and flat as a result of siltation from the Kobuk and Noatuk Rivers. Depths average 12 to 14m (39-46 ft).

The continental shelf of the Alaskan Beaufort Sea is relatively narrow, averaging about 80 km (50 mi) in width. The shelf break occurs at depths of 70 to 75m (230-250 ft). The slope gradients along the shelf are even more gentle than those in the Chukchi. Consequently, relatively shallow water may be found for considerable distances offshore. At Harrison Bay, for example, the 20m (66 ft) isobath lies as much as 72 km (45 mi) offshore. In the eastern Beaufort, the slope is somewhat steeper. At Camden Bay, the 20m (66 ft) isobath lies 18.5 km (11 mi) offshore.

The numerous lagoons formed by the barrier islands along the Beaufort and Chukchi coasts are relatively shallow. In Simpson Lagoon, the maximum water depths are 2.0 to 2.3m (6.5 to 7.5 ft). Between Midway Island and Prudhoe Bay, depths range up to 8.5m (28 ft). South of Flaxman Island, maximum depths are 2.3m (7.5 ft).

B. GENERAL CLIMATOLOGY

The climate of Alaska's north coast is classified as arctic by the National Weather Service. Summer weather is characterized by cool marine winds, frequent but light precipitation and considerable cloudiness and fog. In winter, the cloudiness decreases and very cold winds prevail. A light snow cover is established by mid-September which persists until June or July. Below freezing air temperatures are the rule except in June, July, August and early September when temperatures are normally about 4°C (40°F). Mid-winter temperatures of minus 25°C to minus 28°C (minus 15°F to minus 20°F) are typical. Persistent winter winds may drive the temperatures to minus 50°C (minus 60°F) or lower, making any outdoor work difficult and often hazardous.

Most of our present knowledge of the Alaskan Arctic climate is limited by a rather short data base. Systematic collection of meteorological information in the area was not begun until after World War II, when the Defense Department established military facilities along Alaska's northern coast. Prior to this, only scant information was available from native records, whaling ships, expeditions, and occasional forays by aircraft.

Data from offshore areas are even more limited than the immediate coast. Relatively few vessels, except for occasional icebreakers, ever enter the Alaskan Arctic, especially in winter. Summer marine traffic is normally limited to open water adjacent to coastal areas. Natural floating ice islands and multi-year floes have received limited use as offshore observation stations. The relatively transient nature of these islands and floes, however, limits their usefulness in assembling a coherent picture of offshore climatic phenomena.

Vivid testimony to our lack of knowledge in the Arctic offshore areas of Alaska is found in the recently published Climatic Atlas of the Chukchi and Beaufort Seas (Brower et al., 1977). This atlas is one of three such volumes prepared for the NOAA/BLM Outer Continental Shelf Environmental Assessment Program (OCSEAP). Companion volumes include the Bering Sea and Gulf of Alaska. The intent of this work was to provide a detailed climatic profile of the marine and coastal regions of Alaska. Although the Bering Sea and Gulf of Alaska volumes are relatively complete in this regard, the Chukchi-Beaufort Sea volume contains page after page of blank graphs with the notation "Insufficient Data." More recent information exists, but it has not yet been compiled in a form for analysis.

Remaining sections of this chapter discuss the climatic phenomena of Alaska's north coast with particular reference to those aspects which may affect offshore petroleum development. Due to the sparsity of data for offshore areas, much of the information is drawn from coastal stations such as Barter Island, Barrow, and Kotzebue. In general, this information is sufficient to generally describe conditions some distance offshore.

1. Temperature

Persistently low temperatures are one of the most conspicuous and troublesome aspects of the Arctic climate. In winter, the sun is either below the horizon continuously, or remains so low that very little solar radiation reaches the ground. In summer, the maximum solar elevation is about 42^{o}, but extensive cloud cover reflects much of the incident shortwave radiation. Monthly radiation values vary from near zero during the winter to an average of about 71 kilojoules/cm^2 per month in June (Swift et al, 1974). Lacking solar radiation, heat input to the Arctic air is thus primarily derived from longwave radiation emanating from the surface.

As a result of this phenomenon, air temperatures offshore and along the coast tend to be somewhat milder and uniform than at inland locations. Air temperatures above the polar pack ice, for example, are not as cold as readings reached in Alaska's interior because of heat radiated by the relatively warm water below the ice.

Table 1-1 is a listing of representative temperature information for nine coastal stations along the Chukchi and Beaufort Seas. These locations are shown in Figures 1-1 and 1-2. An examination of the data in Table 1-1 shows that coastal stations along the lower Chukchi are, on the average, slightly warmer than stations along the Beaufort and upper Chukchi. Both locations, nevertheless, are subject to similar extremes in temperature. It is also interesting to note that

Table 1-1. Arctic Coastal Temperatures

Station	Mean[1] Annual °F (°C)	Summer[2] Season Max. °F (°C)	Winter[2] Season. Max. °F (°C)	Record[1] High °F (°C)	Record[1] Low °F (°C)	Mean No. of Days 32° F (0° C) and below[2]
1 Tin City	19.9 (-6.7)	50 (10.0)	-11 (-23.9)	75.0 (23.9)	-44.0 (-42.2)	---
2 Kotzebue	20.8 (-6.2)	61 (16.1)	-13 (-24.9)	84.9 (29.4)	-52.1 (-46.7)	251
3 Cape Lisburne	18.0 (-7.8)	52 (11.1)	-20 (-28.9)	73.9 (23.3)	-47.0 (-43.9)	268
4 Point Lay	12.9 (-10.6)	53 (11.6)	-27 (-32.7)	78.1 (25.6)	-54.9 (-48.3)	284
5 Wainwright	10.8 (-11.8)	50 (10.0)	-24 (-31.1)	80.1 (26.7)	-56.0 (-48.9)	306
6 Barrow	9.3 (-12.6)	45 (7.2)	-24 (-31.1)	78.1 (25.6)	-56.0 (-48.9)	324
7 Lonely Point	9.3 (-12.6)	---	---	78.1 (25.6)	-53.0 (-47.2)	---
8 Oliktok	8.8 (-12.9)	---	---	75.0 (23.9)	-49.0 (-45.0)	---
9 Barter Island	10.0 (-12.2)	48 (8.9)	-26 (-32.2)	78.1 (25.6)	-59.1 (-50.6)	311

[1] Data from Brower et al. (1977)
[2] Data from Swift et al. (1974)

there are less than 90 days on which temperatures exceed the freezing point at all locations, and along the Beaufort coast, there are less than 60 days.

From an operational standpoint, the temperature resulting from wind chill is a more effective measure of the ability of humans to work in the Arctic environment because it combines the effect of wind and temperature on heat loss. As will be discussed later, persistent winds are a common feature of the Arctic coast. At Barrow, for example, a no wind condition exists only 1.3 percent of the time (Searby and Hunter, 1971). Table 1-2 is a wind chill chart for temperatures from 0°C to minus 50°C (32°F to minus 58°F) and wind speeds of 0 to 50 mph.

Using hourly values of temperature and corresponding surface wind reports for Barrow, Searby and Hunter (1971) developed probability curves for equivalent chill temperatures on a monthly basis (Figure 1-3). The curves are generally applicable to coastal locations along the Beaufort Sea. With respect to outdoor working conditions, these curves illustrate the high probability of encountering dangerous temperatures during almost all times of the year. Subfreezing equivalent temperatures, for example, may be encountered with a 90-percent probability during all months except July and August. Considerable danger from freezing exists when equivalent temperatures drop below minus 36°C (minus 24°F). Such conditions exist at least half of the time from November through March.

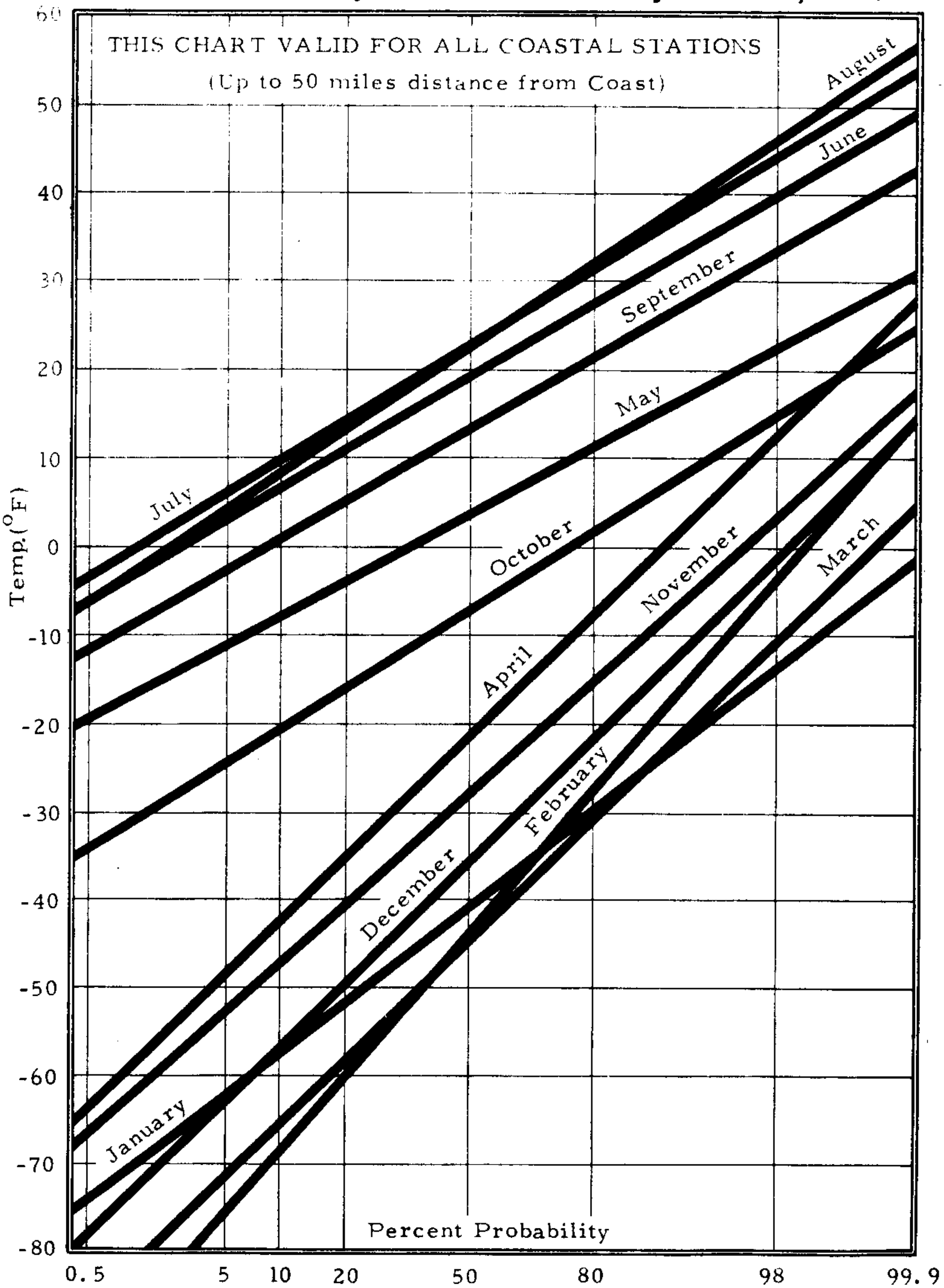
Table 1-2. Windchill Chart (Searby & Hunter, 1971)

	LOCAL TEMPERATURE (°F)										
WIND SPEED (MPH)	32	23	14	5	-4	-13	-22	-31	-40	-49	-58
	EQUIVALENT TEMPERATURE										
CALM	32	23	14	5	-4	-13	-22	-31	-40	-49	-58
5	29	20	10	1	-9	-18	-28	-37	-47	-56	-65
10	18	7	-4	-15	-26	-37	-48	-59	-70	-81	-92
15	13	-1	-13	-25	-37	-49	-61	-73	-85	-97	-109
20	7	-6	-19	-32	-44	-57	-70	-83	-96	-109	-121
25	3	-10	-24	-37	-50	-64	-77	-90	-104	-117	-130
30	1	-13	-27	-41	-54	-68	-82	-97	-109	-123	-137
35	-1	-15	-29	-43	-57	-71	-85	-99	-113	-127	-142
40	-3	-17	-31	-45	-59	-74	-87	-102	-116	-131	-145
45	-3	-18	-32	-46	-61	-75	-89	-104	-118	-132	-147
50	-4	-18	-33	-47	-62	-76	-91	-105	-120	-134	-148

LITTLE DANGER FOR PROPERLY CLOTHED PERSONS | CONSIDERABLE DANGER | VERY GREAT DANGER

DANGER FROM FREEZING OF EXPOSED FLESH

Figure 1-3. Equivalent Chill Temperature at Barrow, Alaska—Percent Probability of Occurrence (Searby & Hunter, 1971)



Offshore work in the Arctic may expose personnel to the possibility of immersion hypothermia which involves loss of body heat to water. The survival time of human beings in the sea is directly related to sea surface temperatures, and to a lesser extent, human behavior and condition. Table 1-3 depicts approximate survival times due to immersion hypothermia.

Table 1-3. Approximate Survival Time Versus Water Temperature

Water Temperature (°F)	Exhaustion or Unconsciousness	Expected Time of Survival
32.5 (and below)	15 min	15 - 45 min
32.5 - 40.0	15 - 30 min	30 - 90 min
40 - 50	30 - 60 min	1 - 3 hrs
50 - 60	1 - 2 hrs	1 - 6 hrs
60 - 70	2 - 7 hrs	2 - 40 hrs
70 - 80	3 - 12 hrs	3 - Indefinite
80	Indefinite	Indefinite

Source: Searby and Hunter (1971)

The survival times given are only first order approximations since there are many uncontrollable physiological factors. Nevertheless, it is clear that any immersion in Arctic waters where temperatures remain close to 0°C (32°F) year round is a very serious matter. For human transport to offshore facilities by boats, aircraft or over ice, accidents involving immersion will require prompt emergency rescue response.

2. Precipitation

Precipitation over most of the Arctic coast is very light, usually less than ten inches annually in the Beaufort and northern Chukchi Seas. Kotzebue Sound in the southern Chukchi Sea can receive up to 20 in. of precipitation each year as a result of storms which migrate northward across the Bering Strait. The arid to sub-arid conditions which prevail are due mainly to low temperatures which prevent water vapor buildup in the atmosphere, and secondarily to ice cover which prevents the evaporation of water below it. As a result, the relative humidity is generally high (60-90%) but the absolute humidity is very low.

Rain accounts for the major part of the annual precipitation. July and August are the wettest months because they are the warmest months and also because the protective ice cover has melted. Snow may fall during any month of the year and the ground is normally snow covered from mid-September until June. Total annual snowfall averages 12-60 in. along the North Slope coastal stations. To the south, snowfall increases to a maximum of 20-70 in. in Kotzebue Sound. Southern areas are also more prone to blizzard conditions because of occasional cyclonic storms which pass through the region in the winter.

Other precipitation phenomena include rime ice, a deposit of granular ice which occurs over coastal regions throughout much of the year and hoarfrost in winter. Representative precipitation data are shown in Table 1-4. Station locations for these data can be found in Figures 1-1 and 1-2.

Table 1-4. Arctic Coastal Precipitation (Swift et al., 1974)

Station	Liquid Precipitation (Inches)				Snow (Inches)		
	Annual Mean	Monthly Maximum	24-Hour Maximum	Mean Number of Days =.01 or more	Annual Mean	Monthly Maximum	24-Hour Maximum
1. Tin City	19.2	7.7 (Aug)	2.0 (Jul)	143	75	24.7 (Sept)	8.6 (Apr) (Sept)
2. Kotzebue	8.2	5.2 (Aug)	1.8 (Jul)	110	47	60.5 (Jan)	8.6 (Mar)
3. Cape Lisburne	14.7	7.0 (Aug)	1.8 (Aug)	---	60	---	11.0 (Nov)
4. Point Lay	6.6	6.2	1.5	---	20	---	---
5. Wainwright	5.0	9.3 (Aug)	4.0 (Jul) (Aug)	---	12	12.0 (Oct)	---
6. Barrow	4.3	2.8 (Aug)	1.0 (Oct)	74	29	26.0 (Apr)	15.0 (Oct)
7. Barter Island	6.3	4.9 (Sept)	2.3 (Jul)	93	46	36.0 (Sept)	17.0 (Sept)

3. Surface Winds

Surface winds along the Arctic coast tend to blow at a fairly constant rate throughout the year. Yearly means of 10-15 mph are typical of all exposed coastal locations and completely calm conditions exist less than 5 percent of the time at most coastal stations. Table 1-5 summarizes surface wind conditions for stations along the Beaufort and Chukchi coasts.

High winds may occur at any time of the year although maximum velocities have occurred historically in the coldest months. Tin City and Barter Island tend to be the worst locations for strong steady winds. Both stations experience gale-force winds about 5 percent of the time during winter. In contrast, the other coastal stations experience such winter winds only 1 percent of the time, or less.

The persistent Arctic wind can pose a number of operational difficulties for offshore development. Wind chill, previously discussed, is probably the most serious problem. At Kotzebue, for example, winter monthly minimum temperatures of minus 25°C (minus 13°F) coupled with average wind speeds of 15 mph, produce an equivalent chill temperature of minus 45°C (minus 49°F). This wind chill can freeze exposed flesh within one minute. Strong winds have a marked effect on snowfall during the winter months. In addition to driving the snow as it falls, thus creating visibility problems, it also forms deep drifts which hamper surface transport. Wind may also

Table 1-5. Surface Winds at Arctic Coastal Stations (Swift et al., 1974)

Station	Winter		Summer		Fastest Mile		2nd Fastest Mile	
	Prevailing Direction	Mean Speed (mph)	Prevailing Direction	Mean Speed (mph)	Direction	Speed (mph)	Direction	Speed (mph)
1. Tin City	E, NE	20	N, S, SE	15	NW	>65	Several	63
2. Kotzebue	E, SE, NE	13	W	13	SE	93	SE	88
3. Cape Lisburne	E, SE	13	E, NE, SW	12	—	>65	—	55
4. Wainwright	E	—	E, SW	—	—	—	—	—
5. Barrow	E, NE	11	E	12	W	58	W	55
6. Barter Island	W, E	14	E, NE	12	SW	81	W	78

cause a number of ice-related problems. During the summer months, for example, strong offshore winds may drive the pack ice into the nearshore area. This occurs occasionally east of Point Barrow and seriously interrupts the summer barge and shipping routes along the North Slope. Any offshore construction in unprotected areas might also be affected by this phenomenon.

4. Cloud Cover and Visibility

Cloudiness is a prevalent condition along the entire Arctic coast. Over 60 percent of the days are cloudy on an annual basis. During the summer and early fall, cloudiness occurs more than 70 percent of the time. Apparently this is due to the presence of open water and higher temperatures. During the summer, cloud types tend to be uniform and colorless stratus.

Fog is the major restriction to visibility in the Arctic. Dense fog can be expected to occur 30 to 100 days each year along the coast. Offshore and inland areas are much less prone to fog. Advection fog is the commonest form along the coast, caused by relatively warm, moist air moving over a cold surface. This situation normally occurs during the open water season in summer and early fall. Areas along the Chukchi Sea coast may have advection fog for up to 15 to 20 days per month in summer (Arctic Institute of North America, 1974). Advection fog tends to persist because of strong temperature inversions, almost always present in the Arctic, which prevent turbulent dissipation.

During winter months, radiation fog is common over coastal and inland areas. It develops under sharp temperature inversions during very cold weather. Radiation fogs are characteristically shallow and low in density. Steam fog is another common coastal phenomenon which is caused by a differential in the air and water temperature. Open water leads, which occur in the fast ice zone adjacent to the coast, are often surrounded by steam fog which appears as a low, clinging layer. In extreme cases, steam fogs may reach a height of 1,500m (5,000 ft) but as a rule, they are shallow and quickly dissipated by the wind.

Under fairly specific conditions, an additional form is ice fog. At temperatures of about minus 37°C (minus 35°F) and lower, water vapor sublimates on hydrocarbon molecules or other suitable nuclei forming an ice crystal fog. Such fogs normally occur when the air is calm in the immediate vicinity of human settlements with heavy water usage. Ice fog may vary from 15 to 150m (500 to 500 ft) in thickness and visibility may be reduced to near zero (Arctic Institute of North America, 1974).

Table 1-6 presents monthly summaries of fog conditions (all types) at three Chukchi Sea coastal locations and at two on the Beaufort coast. It is apparent from the data that there are wide variations in visibility limitations imposed by fog due to both season and location. In general, summer

Table 1-6. Monthly Fog Conditions at Arctic Coastal Stations (Brower et al., 1977)

Table 6. MONTHLY FOG CONDITIONS AT ARCTIC COASTAL STATIONS
(Percent frequency of occurrence based on hourly observations)

Station	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec	Ann
1. Tin City	26.4	31.7	30.4	38.4	42.1	44.4	48.6	37.4	23.1	13.9	16.4	25.5	31.9
2. Kotzebue	4.9	6.5	5.7	7.2	6.9	9.6	5.4	4.7	3.0	3.0	3.6	5.0	5.5
3. Cape Lisburne	8.1	10.5	11.7	13.5	16.6	22.8	18.6	18.8	11.3	5.2	4.4	6.1	12.3
4. Barrow	12.5	13.1	7.9	9.3	17.4	26.4	25.9	25.5	17.7	13.0	10.5	10.4	15.8
5. Barter Island	7.0	7.5	9.1	11.9	24.1	25.8	24.4	32.6	27.0	14.3	9.6	7.3	16.7

fogging conditions are at least twice as bad as winter conditions in most of these places. Secondly, the data appear to indicate that conditions along the Beaufort coast are somewhat more uniform than conditions along the Chukchi. Barrow and Barter Island, for example, have quite similar conditions throughout the year. Tin City and Kotzebue, on the other hand, have radically divergent amounts of fog although the seasonal trends are similar.

Aircraft operations of all types will undoubtedly play a major role in development of the Arctic offshore region. Both ceiling (cloud height) and visibility are extremely important parameters which define flying conditions. Brower et al (1977) have combined ceiling and visibility data into a useful set of tables which can be used to determine the percentage frequency for which various sets of flying minima can be determined. This information is duplicated in Table 1-7.

Searby and Hunter (1971) made a study of flying conditions at seven North Slope airstrips: Prudhoe Bay, Barter Island, Deadhorse, Kavid River, Nora Federal, Pingo, and Sagwon. The general conclusions of their study indicated three aspects of flying weather on the North Slope: first, relatively unfavorable conditions are greatest during the April-May and August-September periods; second, flying conditions tend to improve with distance inland; third, any two locations will not necessarily experience weather conditions below minimum at the same time.

Table 1-7. Visibility and Ceiling Conditions at Arctic Coastal Stations (Brower et al., 1977)

(Percent Frequency of Occurrence, All Months and All Hours)

Station	Visibility (in miles) ≥ 3	≥ 1½	≥ 1	≥ ¾	≥ ½	≥ ¼	≥ 0	Ceiling (in feet)	Station	Visibility (in miles) ≥ 3	≥ 1½	≥ 1	≥ ¾	≥ ½	≥ ¼	≥ 0
Barrow	58	59	60	61	62	62	62	≥ 1,800	Barter Island	61	63	64	65	66	68	68
	61	63	64	64	65	66	66	≥ 1,500		64	66	68	68	70	71	72
	65	67	68	69	69	70	71	≥ 1,200		67	69	71	72	73	74	75
	69	72	73	74	75	76	76	≥ 1,000		70	73	75	76	78	79	80
	71	74	75	76	77	78	78	≥ 900		71	74	76	77	79	80	81
	74	77	79	79	80	81	82	≥ 800		73	76	79	80	81	83	84
	77	80	81	82	83	84	84	≥ 700		74	78	80	82	83	85	86
	79	83	84	85	86	87	88	≥ 600		76	80	82	84	85	87	88
	82	86	88	89	90	91	92	≥ 500		77	81	84	86	88	89	91
	84	88	90	91	93	94	94	≥ 400		78	82	86	87	89	91	92
	85	89	92	93	95	96	97	≥ 300		78	83	87	88	91	93	95
	85	90	92	93	96	98	99	≥ 200		78	83	87	89	92	95	97
	85	90	92	94	96	98	100	≥ 100		78	83	87	89	92	96	98
	85	90	92	94	96	98	100	≥ 0		78	83	87	89	92	96	100
Tin City	52	56	58	59	60	61	62	≥ 1,800	Kotzebue	82	83	84	84	85	85	85
	55	59	61	62	63	64	65	≥ 1,500		84	86	87	87	87	88	88
	57	62	64	65	66	67	68	≥ 1,200		86	88	89	89	90	90	90
	59	64	66	67	68	70	71	≥ 1,000		88	90	91	92	92	93	93
	60	65	68	68	70	71	72	≥ 900		89	91	92	93	93	93	94
	61	67	69	70	72	73	74	≥ 800		90	92	93	94	94	95	95
	62	68	71	72	73	75	76	≥ 700		90	93	94	95	95	96	96
	64	70	73	74	75	77	78	≥ 600		91	94	95	96	96	97	97
	66	72	75	77	78	80	81	≥ 500		92	94	96	96	97	98	98
	67	74	77	79	80	82	83	≥ 400		92	95	96	97	98	98	98
	69	76	80	82	84	86	88	≥ 300		92	95	96	97	98	99	99
	70	78	82	84	87	90	93	≥ 200		92	95	97	97	98	99	99
	70	78	83	85	88	93	97	≥ 100		92	95	97	97	98	99	100
	70	78	83	85	88	93	100	≥ 0		92	95	97	97	98	99	100
								≥ 1,800	Cape Lisburne	65	67	68	68	68	69	69
								≥ 1,500		73	75	76	77	77	77	77
								≥ 1,200		77	80	81	82	82	83	83
								≥ 1,000		80	83	85	81	86	86	87
								≥ 900		82	85	87	87	88	88	88
								≥ 800		84	87	89	90	91	91	91
								≥ 700		85	89	91	92	93	93	93
								≥ 600		86	91	93	94	94	95	95
								≥ 500		87	92	94	95	96	96	97
								≥ 400		88	92	95	96	97	98	98
								≥ 300		88	93	96	97	98	99	99
								≥ 200		88	93	96	97	98	99	100
								≥ 100		88	93	96	97	98	99	100
								≥ 0		88	93	96	97	98	99	100

5. Optical Phenomena

A number of optical phenomena are present in the Arctic which make certain operations more difficult to accomplish than in areas of more temperate climate. Unfortunately, there are no quantitative data available with which to judge the probability of occurrence of such events. However, they are sufficiently common to be credited with numerous accidents, particularly those involving aircraft. Before proceeding with a discussion of these phenomena, it is useful to examine the natural light cycle in the Arctic because of its unique nature and because it is responsible for a number of these optical problems. The northern Alaska coast receives constant sunlight for about two and one half months during the summer. At Barrow, the sun is above the horizon continuously from May 10 to August 2. Conversely, there is a long period of winter darkness. At Barrow, the sun is below the horizon from November 18 to January 23. However, during the winter months when the sun is not more than six degrees below the horizon, there is sufficient twilight to carry on a number of activities without artificial light. Figure 1-4 shows the daylight/darkness cycle at Barrow. However, as mentioned above, there is a twilight period which extends into the shaded area on both sides of the graph.

The following optical phenomena frequently occur in the Alaskan Arctic. Information for this section was gathered from Swift et al (1974).

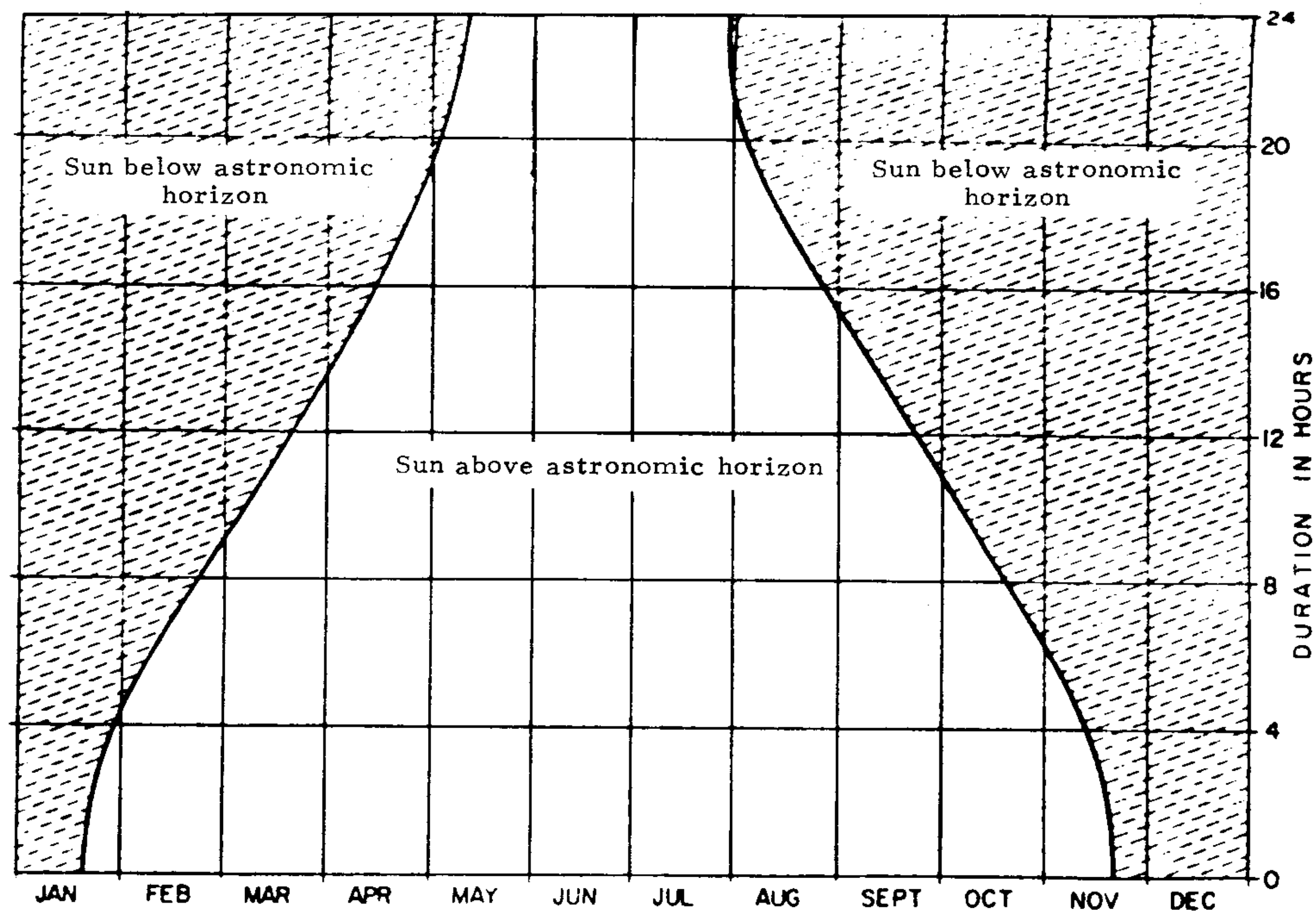


Figure 1-4. Daylight/Darkness Cycle at Barrow, Alaska (Arctic Institute of North America, 1974)

a. Terrestrial Refraction (Mirages)

Atmospheric temperature inversions, which are a common Arctic feature, cause a greater than normal refraction in the lower atmosphere. This results in distortion of shapes and positions of objects seen at a distance. Objects which normally lie beyond the horizon may be lifted into view (looming) and objects normally visible may fall below the horizon (sinking).

b. Terrestrial Scintillation (Optical Haze)

Optical haze is produced by irregular refraction effects. This is due to the passage, across the line of sight, of air parcels whose densities differ slightly from that of their surroundings. This effect is caused normally by isolational heating of the earth's surface resulting in thermal turbulence in the surface layer of air. Optical haze is manifested by a blurred or distorted landscape. In temperate climates, this phenomenon may be observed as "heat waves" which rise from asphalt surfaces on warm, sunny days.

c. Ice and Snow Blink (Sky Map)

Snow blink appears as a bright, white glare on the underside of a cloud layer. It is produced by light reflection from a snow or ice-covered surface.

d. Whiteout

Whiteout is a phenomenon in which the observer appears to be engulfed in a uniformly white glow. Neither shadows, clouds, nor horizon are discernible and depth perception and orientation are completely lost. Two conditions produce whiteout: 1) a diffuse, shadowless illumination; and 2) a uniformly monochromatic white surface. Both conditions commonly occur in the Arctic.

Whiteout has been known to occur under a cloud ceiling in a crystal-clear atmosphere with ample, comfortable light, and a visual field filled with trees, telephone poles, quonset huts, and oil drums. However, the probability of such an occurrence is considerably lessened if mountains or patches of sky are visible.

Whiteout is a serious problem for pilots in landing, take-off and taxiing. Low flying, especially at altitudes of 300m (984 ft), is particularly hazardous and has resulted in numerous accidents. Ground activities, including walking and vehicle operation, may also be affected.

e. Snow Blindness (Niphablepsia)

Snow blindness is a medical condition characterized by impaired vision or temporary blindness. Caused by reflection of ultraviolet light from snow surfaces, it is a serious problem in the Arctic because of low sun elevations which create a greater incidence of sunlight reflection. Northern sunlight also contains a higher percentage of ultraviolet than encountered at lower latitudes.

C. SEA ICE

Sea ice is the most pervasive feature of the Arctic offshore environment. With the exception of a narrow band of open water close to the coast each summer, sea ice dominates the Arctic Ocean at all times. It is a dynamic feature, in a nearly continuous state of motion or potential motion. Distant meteorological and oceanographic events may have profound effects on local movement because of the ability of ice to transmit forces may miles. Knowledge of the mechanisms responsible for such ice movements is still rudimentary.

As an engineering material, sea ice poses numerous challenges resulting from the variety of physical states, shapes, sizes, and strengths which it exhibits. Strength, for example, is determined by a multitude of conditions including temperature salinity, age, crystal structure, gas content, rate of deformation, shape and size. These variables are not all related and their combined effects have yet to be quantified into precise engineering formulas which can be used to determine the forces which ice might exert on offshore structures.

In spite of certain fundamental gaps in our knowledge regarding the sea ice environment, considerable information has been developed which lays the groundwork for the solution of many offshore development problems. Industry, academic and government programs within the past five to ten years have added a major increment to our knowledge of sea ice conditions in the Alaskan Arctic. This section of the report briefly summarizes those conditions. (A more complete discussion of sea ice problems, as related to offshore development, is given in Section IV of this report.)

1. Sea Ice Zonation

For ease of discussion, the sea ice environment can be divided into a number of zones, each having more or less distinct properties from the others. Profiles of this zonation are shown for late winter and spring conditions in the Beaufort Sea (Figures 1-5 and 1-6). It should be recognized that this is an arbitrary characterization, and that the boundaries shown are subject to considerable variability in time and space. Major features of each zone are discussed below.

a. Landfast Ice Zone

The landfast ice zone can be further subdivided into: (1) the bottom-fast ice zone; and (2) the floating-fast ice zone, (Figure 1-6). The bottom-fast ice zone is formed by ice which is in continuous contact with both the shoreline and the sea floor. The extent of the bottom-fast zone increases seaward during the winter months as more ice is frozen solid from the surface to the sea floor. Its maximum extent is generally at the 2m (6.6 ft) isobath, which may vary from a few meters to several kilometers offshore.

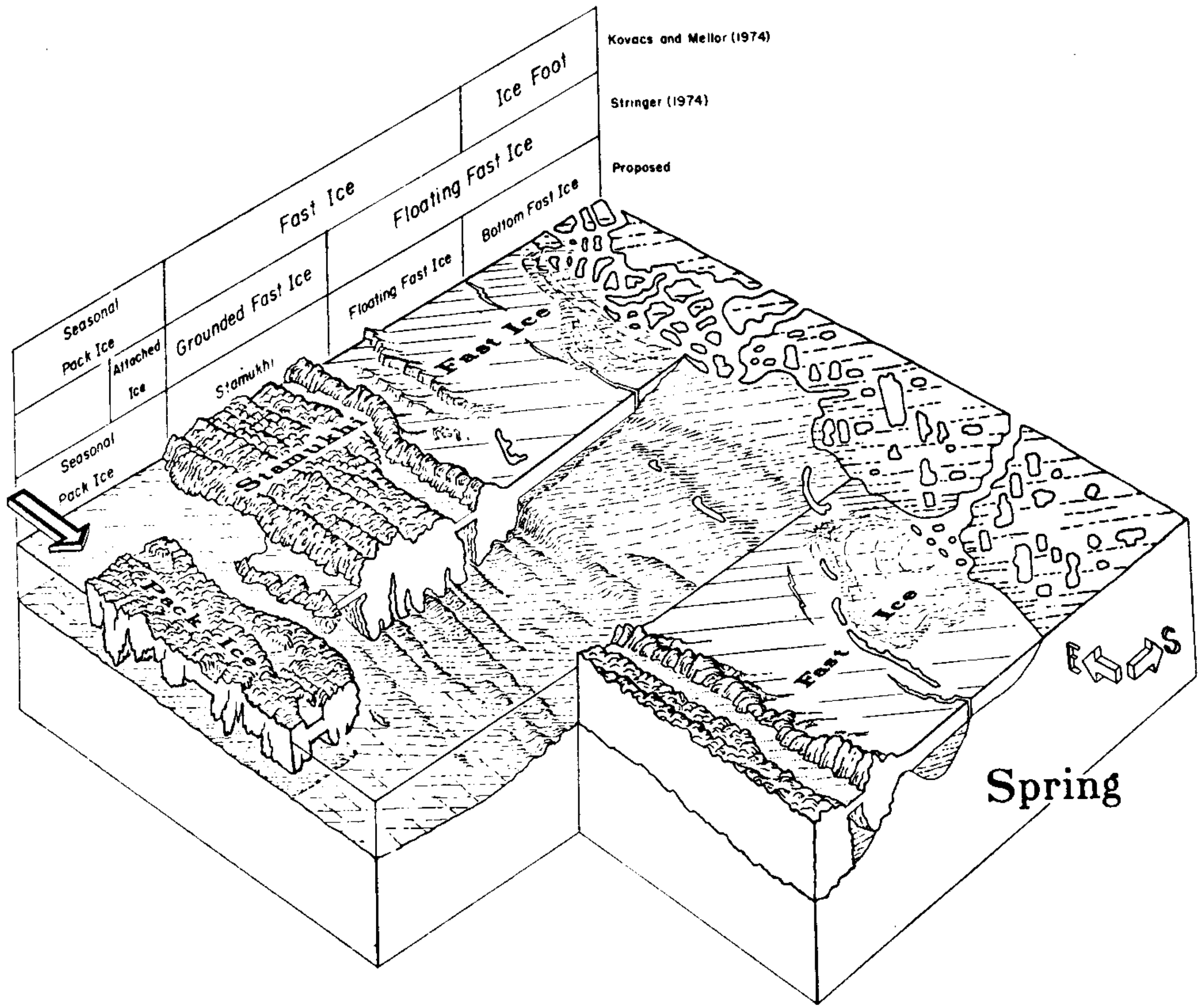


Figure 1-5. Spring Ice Zonation of the Alaska Beaufort Sea (Reimnitz, Toimil and Barnes, 1977)

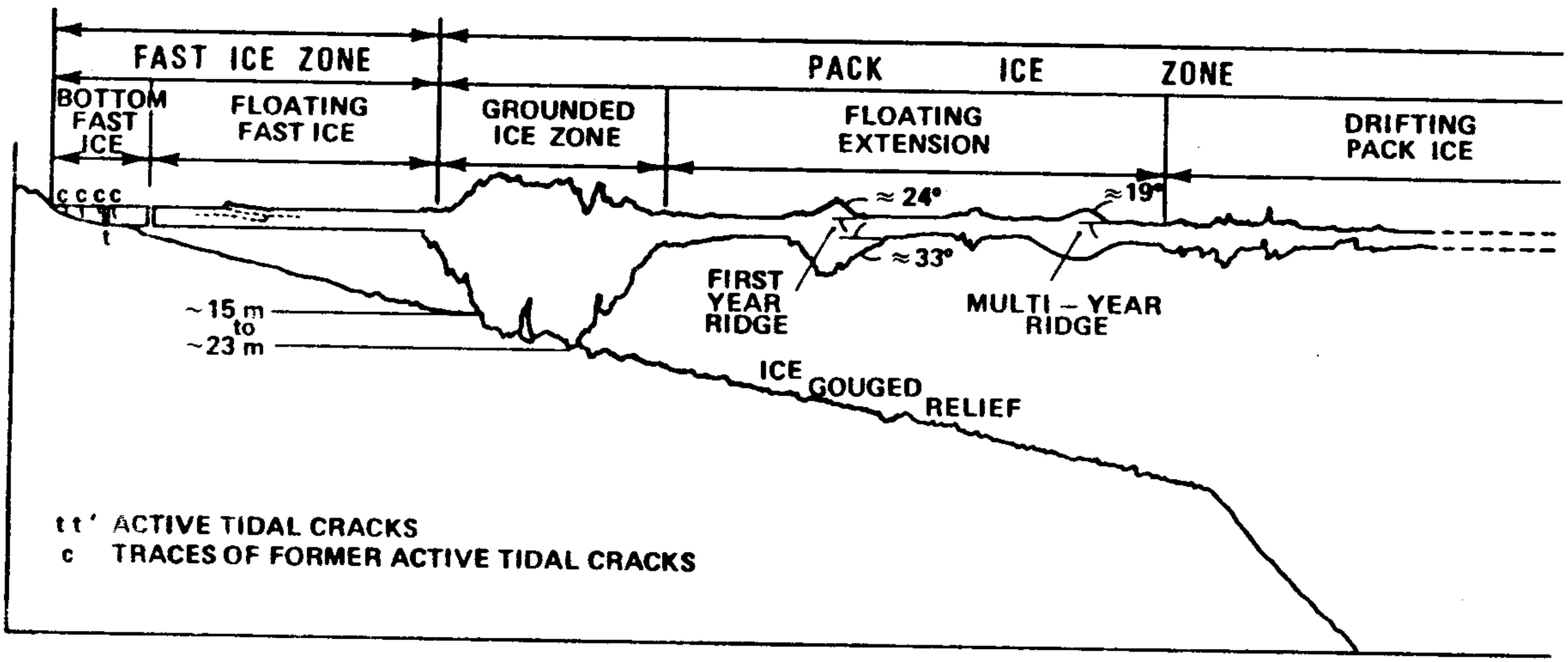


Figure 1-6. Late Winter Ice Zonation of the Alaska Beaufort Sea (Shapiro & Barry, 1978)

The bottom-fast zone is relatively smooth in appearance although small grounded ice features and pressure ridges provide some surface relief. The surface of the ice is also marked with tidal cracks which result from flexure of the ice in response to ocean tides and other water motions. Many such cracks are formed as the margin of the zone moves seaward. Older cracks refreeze, forming irregular scars.

Large scale motion within the bottom-fast zone is believed to be negligible during the period of time when it is in close contact with the bottom (Shapiro and Barry, 1978). However, prior to fall freeze-up and after the spring thaw begins, appreciable movement is possible. There is also some evidence of localized ice motion even during winter months. Hanson et al (1978) report several instances of ice movement across beaches near Barrow, Alaska, which occurred in December and January (1977-78). This phenomenon known as "ice push" resulted in two barrier islands being completely overridden by bottom-fast ice at least 60 cm (2 ft) thick. It is attributed to either wind stress or to abnormal pressure from the offshore pack ice.

The floating-fast ice zone (Figure 1-6) extends from the edge of the bottom-fast ice, in a seaward direction, to the boundary of the zone of grounded ridges. The seaward limit of this zone is normally taken as the 18m (60 ft) isobath, although considerable variability occurs from year to year and at different locations along the coast. In the Beaufort Sea, a significant part of the area occupied by the floating-fast ice zone lies shoreward of the barrier islands. In this protected area, the ice is primarily first-year ice, with some fragments of multi-year drift ice embedded in it. Small pressure and shear ridges may also be found within the fast ice zone. In areas unprotected by islands, sizeable pieces of multi-year floes and ice-island fragments may be incorporated to create formidable ice masses (Kovacs, 1976). If grounded, these features help to stabilize the first-year ice.

During the winter months, movement of ice in this zone is an item of considerable interest for offshore development. This is especially true of the Beaufort coast because of potential near-term development prospects. Inside the barrier islands, where the floating ice is relatively protected, net winter movement is believed to be in the range of a few meters (Shapiro and Barry, 1978). Such motion is attributed to thermal expansion and contraction, or to larger meteorological events. During freeze-up, wind and currents can move the young ice sheet distances of several hundred meters. There is less concern during this period, however, because the ice is thin and relatively weak.

Outside of the barrier islands, two groups of investigators have measured winter ice movement. The oil industry has completed four years (1975-1979) of ice movement studies at locations between Flaxman Island and Harrison Bay. They reported net winter movement on the order of tens of meters outside the barrier island (Cox, 1978). Weeks and Kovacs (1977) monitored movements of floating-fast ice sheets during March, April, and May (1976-77) in the vicinity of Narwhal Island (northeast of Prudhoe Bay). They observed gradual maximum movements of more than 60m (200 ft) during a winter season. It is difficult to draw even a tentative conclusion from this limited set of measurements, however, because the floating ice sheet seaward of Narwhal Island is relatively narrow (less than 15 km (9 mi) wide). In other coastal locations the floating ice zone may extend for distances up to 80 km (50 mi). Thus, it is logical to suspect that larger movements are possible. Weeks (1978) has subsequently stated that during a winter season cumulative movements in excess of 100m (330 ft) must be presumed possible anywhere within the floating-fast ice zone. However, in stabilized or protected areas, deformation rates are slow and do not cause override or pile-up events.

No measurements of floating-fast ice movement are available for the Chukchi Sea except in the most northerly part near Point Barrow. It is presumed that considerable ice motion occurs at most locations along the coast with the possible exception of inner Kotzebue Sound. This is based on the fact that winter and spring ice processes in the Chukchi Sea are much more dynamic than in the Beaufort Sea. The Chukchi has a relatively narrow margin of fast ice which is in contact with a constantly southward moving drift ice system. This system has a shearing effect on the edge of the fast ice sheet.

The inner portion of Kotzebue Sound has a much wider margin of fast ice than the exposed coast. Nevertheless, the outer edge of this ice sheet is also subject to drift ice shear which may, in turn, create some instability in the attached ice.

A final comment regarding the floating-fast ice zone concerns its crystalline structure. Recent work by a variety of investigators is summarized in Shapiro and Barry (1978). Briefly, previous studies of the formation of sea ice had shown that crystals which compose the ice sheet are elongated normal to the plane of the ice sheet and parallel to the direction of growth such that the crystallographic c-axis lies in a horizontal plane. Subsequent work showed that the c-axis is not randomly oriented in the horizontal but, instead, tends to align in preferred directions. More recent investigations in the Beaufort Sea have shown that there is a consistent orientation in the horizontal plane of the c-axis of the crystals which form the land fast ice sheet. Furthermore, this alignment may extend for tens of kilometers. Available data indicate that this alignment reflects mean current patterns in the area.

These findings have significant implications for offshore development. For example: (1) The preferred alignment causes the strength of the ice to be different in different directions. Perfect alignment tends to increase the compressive strength of the ice in some directions so that the maximum force which ice can exert against a structure will also be increased; (2) Thermal expansion and contraction of the ice may be directionally dependent on the crystal orientation (Shapiro and Barry, 1978).

b. Pack Ice Zone

Seaward of the fast ice zone lies the pack ice zone (Figure 1-6) which has three subdivisions within it: the zone of grounded ridges; the floating extension; the drifting polar pack ice. Before discussing the characteristics of each subdivision, it is worthwhile to examine a number of major ice features which may occur within the general limits of the pack ice zone.

(1) Pressure Ridges. Pressure ridges are formed from the interactions or collisions of ice sheets. They consist of a pile of ice blocks which are forced upward to form sails and downward to produce keels. When initially formed (first-year ridges), the ice blocks are poorly bonded to one another and are, consequently, relatively weak. Large ridges which survive the summer melt season are known as multi-year ridges. They are much stronger than first-year ridges because melted water percolates into the open spaces between the ice blocks and subsequently refreezes to form a solid, void-free body of ice.

Pressure ridges may achieve impressive dimensions. Sail heights of free floating ridges as high as 13m (43 ft) have been seen and there is one submarine report of a keel depth extending to 47m (150 ft) in the pack ice zone (Lyons, Unpublished Data). However, the vast majority of ridges have sail heights less than 4m (13 ft) and keels less than 12m (40 ft). Studies of sail heights have shown them to have a negative exponential size distribution (Weeks, 1978). Sail height-to-keel depth ratios have been investigated by Kovacs and Mellor (1974) who found a range from 1:3 to 1:9 in first-year ridges with an average of 1:4.5. Multi-year ridges have an average ratio of 1:3.

Pressure ridges may occur as solitary ice masses surrounded by sheet ice or embedded in heavy multi-year floes of considerable thickness. Quite commonly, however, they occur in a long continuous row which may extend for tens of kilometers (Kovacs and Mellor, 1974). Such ridge systems are created by shearing action between stationary fast ice and moving pack ice. Grounded ridge systems are common in the Beaufort Sea. Kovacs (1976) reported one such feature in a shoal area off Oliktok Point which extended approximately 40 km (25 mi). Ridge systems have been known to survive several seasons in a grounded state. Eventually they float free and break up into massive fragments (floebergs) of considerable strength.

(2) Ice Islands. Ice islands in the Beaufort Sea are tabular icebergs calved from the Ellesmere Island ice shelf and transported to the area by the Pacific Gyral (Figure 1-7).

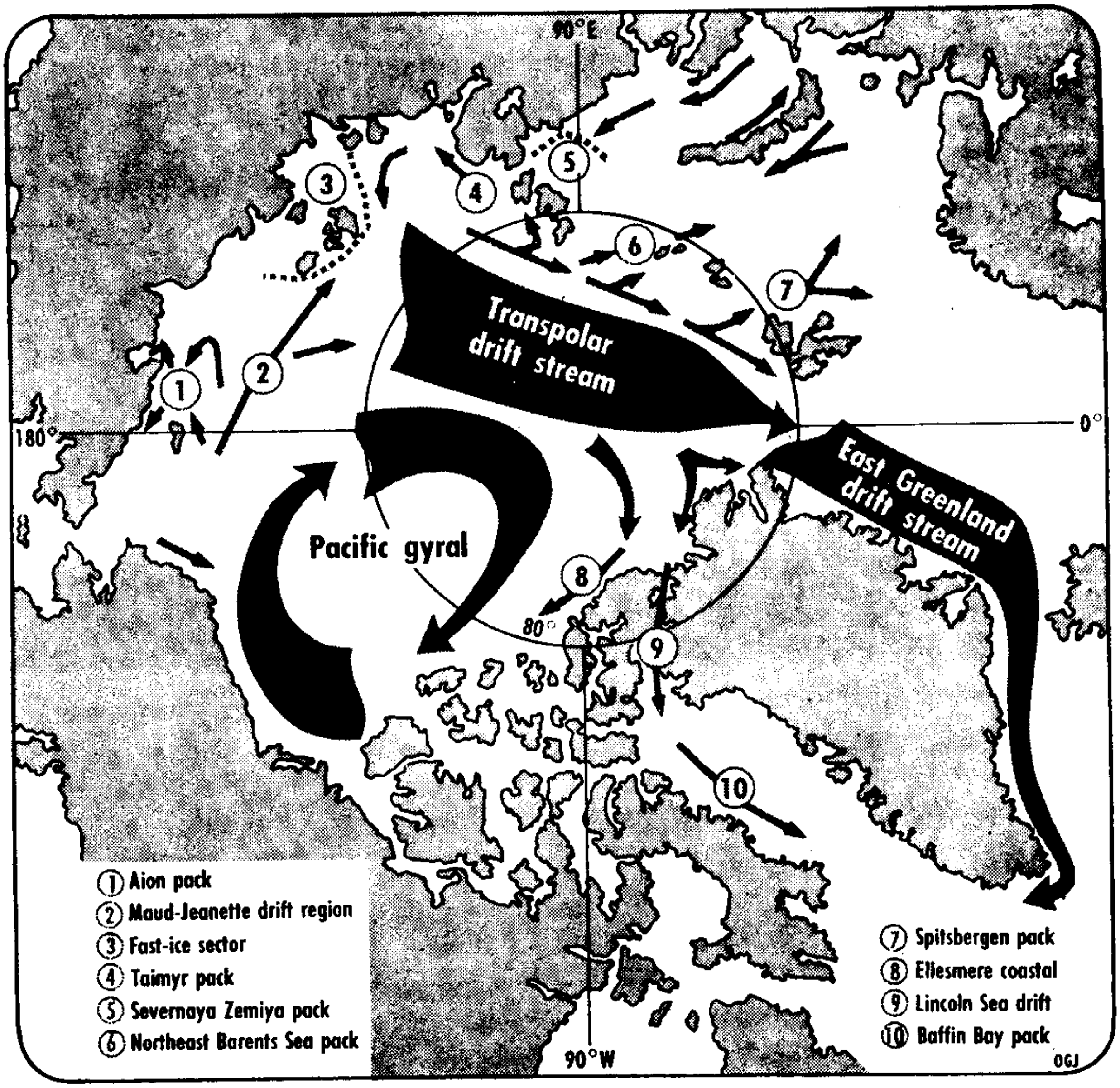


Figure 1-7. Major Polar Drift Streams (Kovacs, 1972)

Ice islands may remain circulating within the Gyral for tens of years (Kovacs and Mellor, 1974).

Ice islands achieve impressive dimensions and it is questionable whether man-made structures other than perhaps artificial islands could survive a direct encounter with a moving large ice island. Those found in Alaskan coastal waters are typically smaller fragments 30 to 100m (100 to 330 ft) across and 12 to 30m (40 to 100 ft) thick (Kovacs and Mellor, 1974). However, they can be much larger in deeper waters. One island known as "T-3," which was used as a drifting scientific station, had initial dimensions of 6 km (4 mi) wide by 14 km (9 mi) long (Weeks, 1978). Ice islands are also very strong since they are composed of fresh water ice. Fortunately, such large ice features would be grounded in the waters of the Beaufort Outer Continental Shelf before hitting any structure.

Little is known about the numbers and distribution of ice islands. An oil industry ice reconnaisance study in 1972 indicated the presence of more than 400 islands along the Alaskan coast (Kovacs and Mellor, 1974). Recent ice island sightings have been less numerous.

Information regarding the ultimate fate of ice islands is scanty. Many become grounded, and are worn down by normal weathering processes and by the abrasion of passing ice. Others may break up into smaller ice islands. Some have escaped the Pacific Gyral system by becoming entrained in the Transpolar Drift Stream and the East Greenland Drift Stream (Figure 1-7).

The first subdivision within the pack ice zone (Figure 1-6) is an area of grounded ridges which marks the location of the first winter interaction between the edge of the land fast ice and the drifting polar pack. This is also called the shear or stamukhi zone. Typically, it occurs in water depths of 15 to 23m (50 to 75 ft), although in some years the depth may extend to the 40m (130 ft) contour.

The grounded ridge zone consists primarily of shear and pressure ridges which are formed by collisions between the moving pack ice and the relatively stable fast ice. The ridges may be interspersed with floes of first-year and multi-year ice and with ice island fragments. Many of the ridges are grounded, and this grounding is thought to provide stability to the fast ice sheet which is attached to the ridges. Grounded ridges are also believed to protect the fast ice from the pack ice by transmitting forces into the sea floor (Shapiro and Barry, 1978).

Large, well-grounded ridges may survive through more than one season; those do tend to be very strong. Many of the ridges do not survive the summer melt, however. They frequently float free and ultimately become entrained in the pack ice.

The zone of grounded ice normally appears as a well-defined band along the Beaufort coast during the winter months. Its width is usually less than 100 km (60 mi) and the ice comprising it shows variable degrees of deformation as one moves along the coast (Weeks, 1978). In the Alaskan Beaufort area, the degree of deformation decreases west of Barter Island.

Between the grounded ridge zone and the drifting pack ice, there is sometimes another zone called the floating extension, which develops from ice that has grown seaward after the grounded ice zone is formed in early winter (Figure 1-6). It is composed of sheet ice and floating ridges which become incorporated as the ice sheet freezes. Because this zone is exposed to constant incursions by moving pack ice, it is an area of active ridge formation, although the ridges do not ground as they do closer to shore. This zone is also characterized by frequent flaw leads (fractures) which form in response to ice stress.

The last zone is the drifting polar pack ice zone which begins at the margin of the continental shelf. The polar pack lies within a clockwise moving circulation system known as the Pacific Gyral (Figure 1-7) which extends from the Beaufort shelf to the North Pole. This circulation is driven by winds of relatively high and constant velocity.

Winter conditions in the pack ice are characterized by large multi-year floes surrounded by thinner first-year ice up to 2.3m (7.5 ft) thick (Kovacs and Mellor, 1974). Multi-year ice is estimated to comprise 60 to 70 percent of the area of the polar pack with first-year ice occupying 25 to 35 percent and open water leads accounting for 1 to 5 percent.

Pressure ridges are a ubiquitous feature of the polar pack. The number of ridges varies from 17 to 32 km (24 to 50 per mi). The majority of these ridges have sail heights of less than 4m (13 ft) and keel depths of less than 15m (50 ft). Much larger features occur occasionally. Wadhams (1977) identified 45 pressure ridge keels with drifts exceeding 30m (100 ft) from a submarine sonar profile of 3,900 km (2,300 mi) length taken northwest of Greenland. The deepest observed keel along this track was 42m (140 ft).

Almost constant motion is one characteristic which distinguishes the polar pack ice from the other ice zones. It is also a feature which makes this area much more hazardous for offshore development than the fast ice zone. Studies done as part of the AIDJEX project, and some done under OCSEAP sponsorship, measured ice drift at various times of the year. Both found that drift in the southern Beaufort Sea paralled the coastline and the mean geostrophic wind field. Winter speeds averaged 20 km (13 mi)/month and up to 80 to 100 km (50 to 62 mi)/month in summer (Shapiro and Barry, 1978).

A brief summary of selected winter ice zone characteristics is found in Table 1-8.

TECHNOLOGY REVIEW OF ARCTIC OFFSHORE OIL/GAS OPERATIONS

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CALIFORNIA 90274

SEPTEMBER 1979

Prepared for

The U.S. Geological Survey

Under

Harry Diamond Laboratories Contract

#DAAG 39-78-C-0091

Table 1-8. Characteristics of Ice Zones in Winter

ZONE	TYPICAL DEPTH RANGE (M)	MAXIMUM OBSERVED MOTION	TYPES OF ICE
BOTTOM FAST ICE	0-2	FEW METERS	FIRST YEAR SHEET SMALL MULTI-YEAR FRAGMENTS
FLOATING FAST ICE	2-15	TENS OF METERS (INSIDE ISLANDS) > 100 METERS (OUTSIDE ISLANDS)	FIRST YEAR SHEET MULTI-YEAR FLOES PRESSURE RIDGES SHEAR RIDGES
GROUNDED RIDGE	15-23	?	PRESSURE RIDGES SHEAR RIDGES
FLOATING EXTENSION	23-SHELF EDGE	> KM/DAY	MULTI-YEAR FLOES SHEET ICE PRESSURE RIDGES SHEAR RIDGES
PACK ICE	BEYOND SHELF	> KM/DAY	MULTI-YEAR FLOES PRESSURE RIDGES ICE ISLANDS SHEAR RIDGES

2. Annual Ice Cycle

Descriptions of cyclic ice phenomena in the Arctic are complicated by the exceptional variability of conditions which can occur from year to year. Not only is there a wide temporal variability in the cycle, but there can be significant differences in the physical events which take place. Any description, therefore, will suffer from a degree of imprecision. With this caveat, the following is a summary of the "typical" sequence of events which occur during an annual ice cycle in the Alaskan Arctic. The dates given may vary by two weeks to a month.

New ice formation in the land-fast zone begins in late September to early October. Under the influence of falling temperatures, ice crystals begin to form and mesh, creating a thin, slushy surface layer. If the sea is rough, this layer will be broken up into circular pieces called pancake ice which eventually fuse to form an ice sheet with a rough surface texture. If the sea is smooth, and the temperature low, the ice will form rapidly into a smooth, textured sheet. During October, the ice continues to thicken and, by the middle or end of the month, may form a continuous sheet which extends beyond the barrier islands in the Beaufort Sea and across Kotzebue Sound in the Chukchi.

As the fast ice is forming, a number of changes begin to occur which affect the location and motion of the polar pack. Normally there is a steepening of the barometric pressure gradient resulting in a wind shift from offshore to onshore. Offshore winds during the summer months tend to prevent the polar pack from encroaching the coast. With this wind shift, however, the pack ice moves toward the shore and the developing fast ice zone. Concurrently, there is an increase in the size of the polar pack due to the addition of new ice at the pack margin. The rate of shoreward motion depends almost entirely on wind conditions. Fall storms may drive the pack toward the coast with both considerable speed and force.

During the early fall, when the land-fast ice sheet is continuous but thin, a zone of interaction is established between the land-fast and moving pack ice. This zone generally forms in depths of 15 to 20m (50 to 66 ft). If the force of the pack ice is of short duration and limited intensity, only the outer edge of the fast ice is affected, resulting in light ridging and low surface relief. If, on the other hand, the force is great and of long duration, spectacular ridging may occur.

By November or December, a zone of grounded ridges is formed which prevents further shoreward incursions by the pack ice and stabilizes the land-fast ice inside the 15m (50 ft) isobath. The land-fast ice is also thickened sufficiently to resist deformation from most forces.

Throughout the winter the zone of ridges may expand seaward. Ridging on the outer edge can still continue, although ridges normally do not become grounded because of increasing water depths. As winter progresses, the polar pack tends to become more massive as loose, multi-year floes are frozen into the main body of the pack. This increases the inertia of the pack so that more force is required to move it toward the shore. Storms decrease during the winter season resulting in an overall effect of less frequent and intense incursions by the pack into the fast ice zone. By March or April, the fast ice may extend to the 30m (100 ft) isobath and may be relatively stable inside that limit.

In late May, rivers along the North Slope begin to melt and flow northward into the Beaufort Sea. Since the estuaries are filled with ice, the river discharge empties onto the surface, resulting in large areas of flooded ice along the coast. This flooding begins the melting cycle, and by early June, melt ponds are found throughout the fast-ice surface. Through June, there is a gradual melting and weakening of the ice.

At about the same time, a lead begins to form in the eastern Beaufort at the mouth of the Mackenzie River. This lead expands rapidly and extends westward to about the Colville River Delta by mid or late July. With the initiation of the summer fast-ice breakup, the pack ice also begins to decay. By the time the fast-ice sheet has disintegrated (July-August), the southern edge of the pack consists of broken floes rather than continuous ice and there is usually a large open lead between the pack and the shore.

Breakup continues along the shore through July and August.

The area of the coast from the Colville River to Point Barrow is normally the last to break up because of prevailing east-northeasterly winds. There is usually some open water from early August to mid or late September along the length of the Beaufort coast. Summer storms, which can push the pack ice into the shore, may occur at any time during this so-called navigable season. Normally, these closures last for only a few days, but in bad years the entire navigable season may last only a few days. Figure 1-8 shows the maximum and average retreat of the polar pack along the Beaufort coast.

3. Long-Term Ice Conditions

Any long-term Arctic endeavor which requires large economic commitments, must consider potential variability in the environment over the development period. In the case of offshore petroleum, the development could last for as long as 40 to 50 years. Unfortunately, inferences about the variability in climate, ice, and oceanographic conditions cannot be based entirely on the recent, more detailed records. It is necessary to consider events over a much longer period to arrive at reasonable inferences about conditions which might occur during several future decades.

As previously noted, the environmental data base for the Alaskan Arctic coast is extremely limited prior to World War II. It has improved enormously in each succeeding decade since then, but almost everything up to that point is dependent

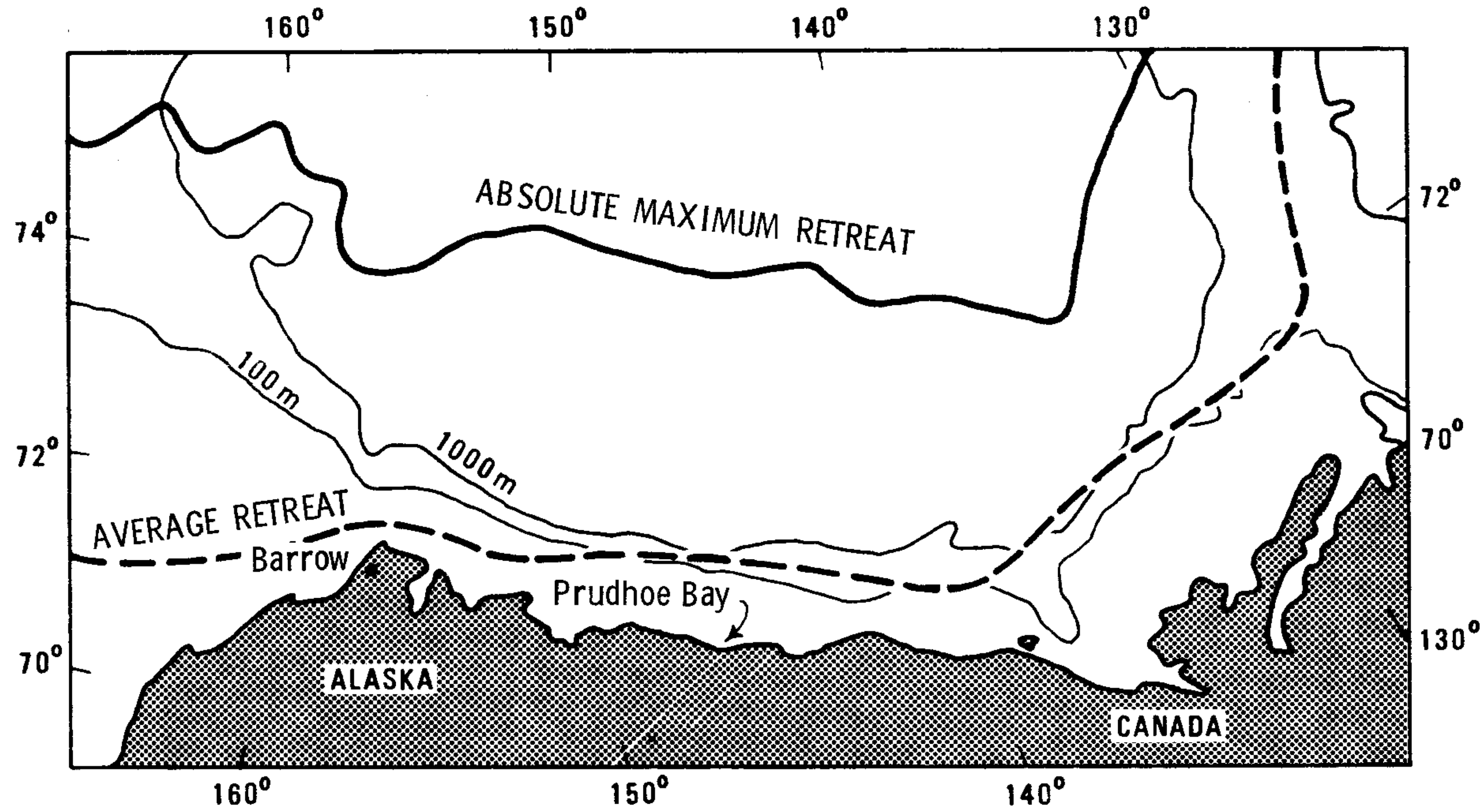


Figure 1-8. Average and Maximum Retreat of Pack Ice From Alaskan Arctic Coast (Shapiro & Barry, 1978)

upon fragmentary records and recollections of native settlers.

Nevertheless, some attempts have been made in the last several years to reconstruct certain environmental events on a longer time scale. Hunt and Naske (1978) have compiled records of early expedition ships, whalers, and trading vessels in an effort to develop historical ice conditions dating from the mid-1800's. Rogers (1978) has examined historical temperature records as a means of correlating ice conditions with temperature. Their results, although not completely satisfactory for extrapolation to long-term forecasts, are indicative of certain trends in climate and ice conditions. Their findings are summarized below.

The Hunt and Naske work was directed toward an examination of the pack ice edge at various times of the year. The edge of the pack is particularly important in summer months because it limits coastal shipping and other logistics when it is close to the coast. The pack could similarly constrain petroleum development activities. Hunt and Naske developed a series of maps, one of which is shown in Figure 1-9, which illustrate differences in the pack location during various time periods from 1860 to 1970. The composite analysis of all the maps indicates that the years from 1940 to 1970 have had significantly more open water in August and September than the period 1860 to 1919. However, temperature records from Barrow, as analyzed by Rogers (1978), indicate a cooling trend since 1921, and this trend has been accompanied by an increasing severity of ice conditions since about 1953.

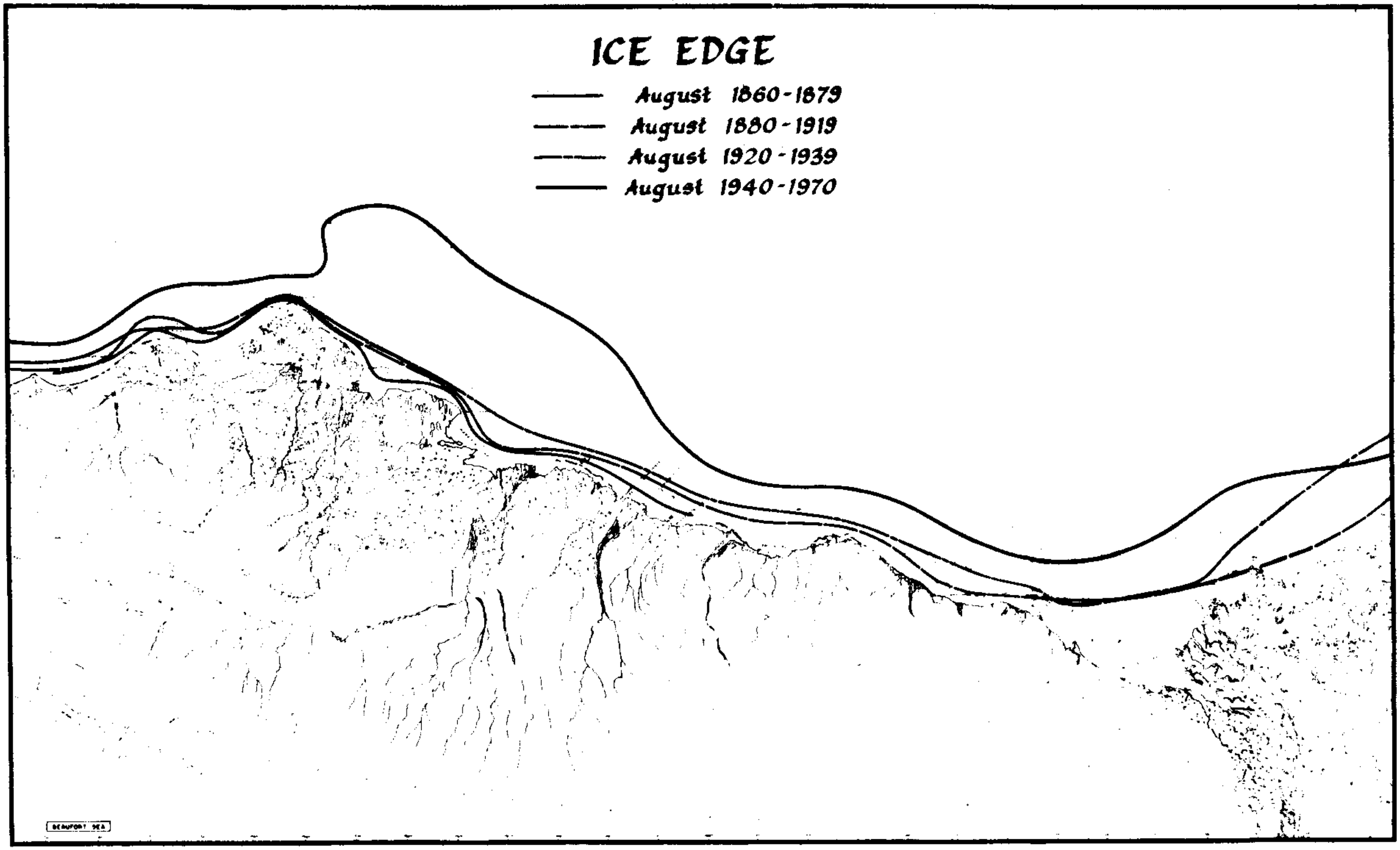


Figure 1-9. Average August Pack Ice Edge, 1860-1970 (Hunt & Naske, 1978)

Differences in Beaufort and Chukchi Sea Ice Conditions

Much of the foregoing information was developed for ice conditions in the Beaufort Sea since the majority of recent research has been focused in that area. In general, the basic conditions and processes described are applicable to the Chukchi as well. Variations are more a matter of degree than kind. The following discussion highlights some of the more fundamental differences which have been observed.

Ice conditions in the Chukchi are slightly less severe than those in the Beaufort. The maximum average thickness of fast ice, for example, is in the range of 1.2 to 1.5m (3.9 - 4.9 ft) (Arctic Institute of North America, 1974). In the Beaufort, the fast ice thickness in late spring is about 2m (6.5 ft). Limited data suggest that pressure ridges are about the same size as in the Beaufort but the zone of grounded ridges is less well-defined. Pressure ridges in the Chukchi tend to occur as discontinuous bands along the coast. The heaviest ridging is found on the north sides of headland areas, where southward moving ice grounds and piles up on shoals which extend seaward (Figure 1-10).

The Chukchi Sea is more dynamic than the Beaufort, particularly in spring and winter (Shapiro and Barry, 1978). After freeze-up, the Beaufort is essentially a vast area of static ice. In contrast, the Chukchi has a much narrower band of contiguous ice (Figure 1-10). The outer edge of this band is being eroded constantly and transported southward toward

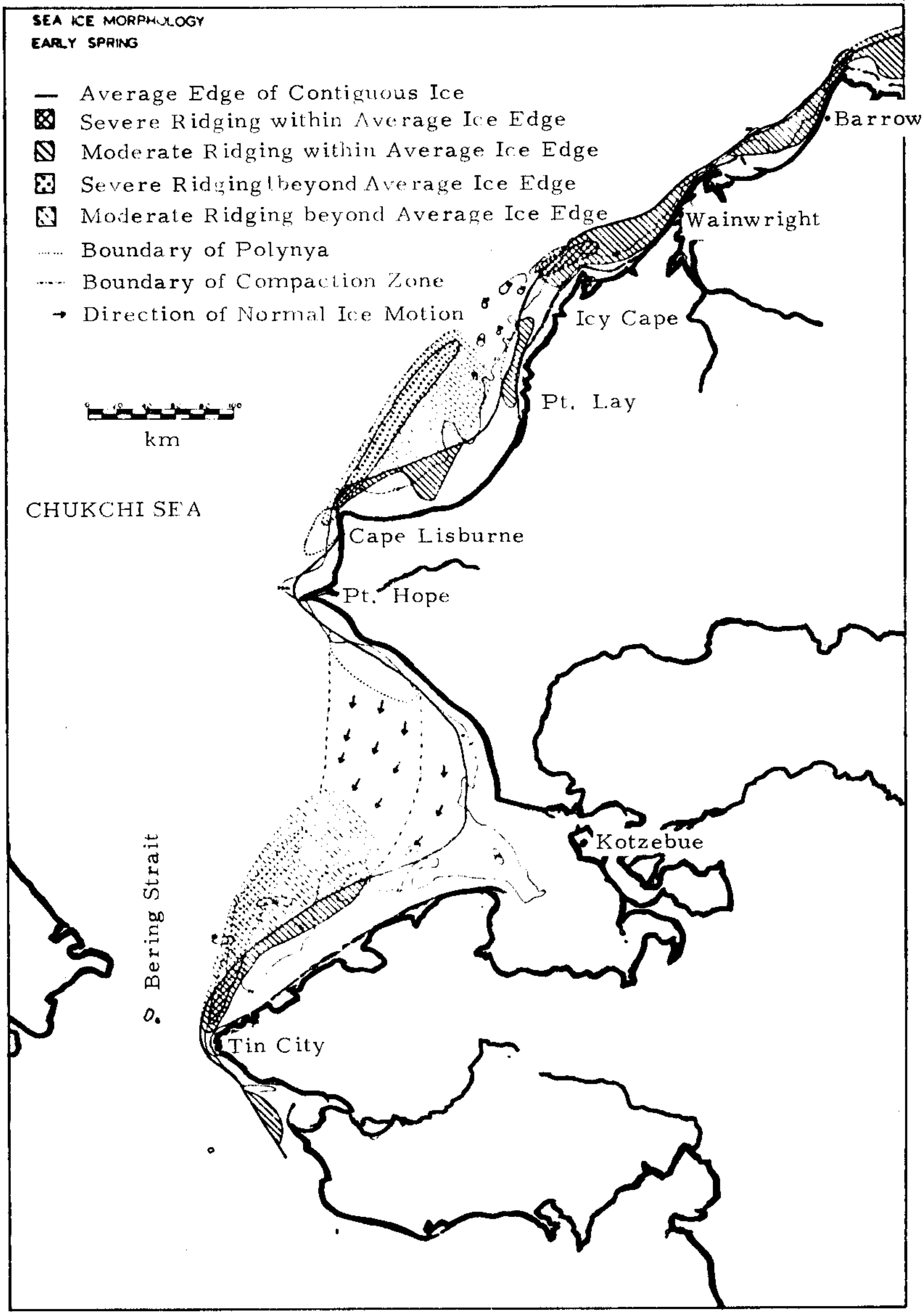


Figure 1-10. Chukchi Sea Ice Morphology (Stringer, 1978)

the Bering Strait. Although some of the ice moves through the Strait, much of it grounds on the seaward jutting shoals, which extend from the numerous capes and headlands (Shariro and Barry, 1978).

The constant southward movement of ice produces another phenomenon which is largely lacking on the Beaufort; namely, open water. Ice which is swept seaward or southward often leaves behind gaps of open water where the ice was formerly attached. On the south side of headland areas, these gaps may be quite large and are known as polynas (Figure 1-10). Along the more exposed edges of the contiguous ice, the gaps are more linear and narrow, and are called flaw leads.

The season cycle in the Chukchi is somewhat similar to that of the Beaufort. In the northeastern Chukchi, freeze-up occurs later and breakup sooner than along the Alaskan Beaufort. This allows a longer period for navigation or offshore construction. By July, for example, there is usually a navigable lead open to Point Barrow (Arctic Institute of North America, 1974). A relatively warm northerly current from the Bering Sea helps to prolong the open water season through most of September. Freeze-up begins in October.

D. OCEANOGRAPHY

This section of the report summarizes existing conditions with respect to waves, currents, and tides in the Beaufort and Chukchi Seas. Relatively few data are yet available for the Chukchi Sea except in the most northern parts, in the vicinity of Barrow.

In temperate locations, where ice is not a factor, waves, currents, and tides are among the most important environmental criteria which must be considered in the design of an offshore structure. In Arctic areas, ice is the foremost problem and will govern the design of almost all structures now contemplated for Arctic use. Nevertheless, serious consideration must still be given to oceanographic parameters, but for somewhat different reasons than in temperate zones. Waves, for example, attain relatively low heights in the Arctic compared to the Gulf of Mexico.

However, waves can still produce serious erosion, and may overtop any structure of insufficient height. Currents are also important with respect to erosion. Tides, particularly meteorological tides (storm surge), can produce large deviations from mean sea level. They are therefore similar to waves because they pose an overtopping threat to offshore structures.

Unfortunately, the existing historical data base for waves, currents, and tides is rather short. The oil industry has completed a one-year program of oceanographic measurements and there are several years of current observations from the OCSEAP program. Existing field data are limited, for the most part, to fragmentary summer observations. Two proprietary studies of oceanographic extremes using hindcast methods have been performed although the results have not yet been verified with measured data.

Given these limitations, it is difficult to develop a coherent picture of wave, current and tidal conditions on the Beaufort Shelf. The following discussion is therefore confined to examples which illustrate the general magnitudes of oceanographic phenomena and should not be construed as design conditions. Table 1-9 summarizes various observations and measurements which are drawn from the discussion that follows.

1. Waves

Wave generation by winds along the Alaskan north coast is limited to the summer open-water season. Since the pack ice retreats a relatively short distance offshore during most summers, the environment is characterized by low, short-period waves except during storms with winds that blow parallel to the coast. Sellman et al (1972) found that 90 percent of the waves in the vicinity of Point Barrow were less than 1m (3 ft) in height. Wiseman et al (1974) made similar observations near Pingok Island and near Point Lay on the northern Chukchi coast. Wave measurements had a characteristic energy peak between 2

Table 1-9. Summary of Beaufort Sea Oceanographic Conditions

Parameter	Normal Range	Extreme Range	Comments
Waves	90% 0-1 m 90% 2-3 sec. period	6*-9** m	Extreme height influenced by water depth and island sheltering. Wave measurements practically non-existent. Waves limited to open water season.
Tides	(+) 10-30 cm (Astronomic)	(+) 3.0 m (-) 1.0 m (Storm Surge)	Extreme -- 25-50 yr recurrence
Currents	5-60 cm/sec (0.1-1.2 knot)	?	Relatively few measurements available, especially under ice.

* Visual observations from ships -- not corroborated with measurements.
** Hindcast for 75 m depths in Canadian Beaufort Sea -- hindcast not calibrated with measured data.

and 3 seconds with significant heights (average of the highest 1/3 of the waves) of 20 to 30 cm (0.6 to 1 ft). Visual observations by numerous sources tend to confirm the mild wave climate which normally prevails during summer.

Much more severe waves can occur under certain circumstances. During some summers, for example, the pack ice has been observed to retreat as far as 190 to 260 km (120 to 160 mi) off the coast. Under these conditions, severe and rapidly moving storms proceeding across the shelf can generate waves over a long fetch. Carsola (1952) made shipboard observations of average wave heights on the order of 4 to 5m (13 to 17 ft) during a storm which occurred near Point Barrow in August, 1951.

High waves have also been reported along the Canadian portion of the Beaufort Shelf. Kovacs and Mellor (1974) describe a storm which occurred near Mackenzie Bay in September, 1970. This storm, which lasted for 36 hours and sustained winds of 104 km (65 mi)/hr, apparently produced offshore waves 9m (30 ft) high as judged from visual observations. Work conducted as part of the Canadian Beaufort Sea Project contained a hindcast of wave conditions in Mackenzie Bay (Berry et al, 1977). Results indicated that waves of about 9 or 10m (30 to 35 ft) could be expected to occur on an average of once every 50 years in areas having water depths greater than 75m (250 ft).

Although the evidence provided above is far from conclusive, it suggests that waves occasionally can occur which are much more severe than normal conditions suggest. However, wave conditions may be very site specific. Along the Alaskan Beaufort coast, shallow water and the presence of barrier islands, may strongly influence the wave climatology. Without a detailed analytic consideration of these factors, it is difficult to predict what influence they will have on waves which are formed in deep water and subsequently move toward the coast.

2. Currents

Although detailed descriptions of the Beaufort Shelf circulation are not yet available, a sufficient number of observations exist to depict the magnitude of events which occur under normal conditions. Most measurements to date have been made in relatively shallow water during the open water season. Nevertheless, some limited data are available for the outer shelf, and under ice, during the winter months.

During the open water season, currents are primarily wind-driven and have relatively small geostrophic and tidal components. In sheltered lagoons and in the shallow areas of the exposed coast, current speeds of less than 50 cm/sec (1.0 kt) have been measured. Seaward of the 50m (165 ft) isobath, slightly higher current speeds have been noted. Hufford (1975), at a water depth of 54m (173 ft) north of Barrow, measured currents up to 60 cm/sec (1.2 kt); Aagaard and Haugen (1977) and Aagaard (unpublished data) measured similar speeds in somewhat deeper water north of Oliktok and Lonely. The dominant direction in these three sets of data was eastward, with periodic, but shorter-duration, westward flow.

Winter measurements beneath ice indicate that tides are the principal driving mechanism. Consequently, speeds are low, in the range of 10 cm/sec (0.2 kt) or less (Barnes and Reimnitz, 1977 and Aagaard and Haugen, 1977). Barnes and Reimnitz (1973) reported one under-ice measurement of 25 cm/sec (0.5 kt). However this was made at a shallow location where the ice is believed to have restricted the tidal flow.

There are few detailed studies of currents in the Chukchi Sea. Nevertheless some information concerning its gross circulation is available from both Russian and American observations. These observations are summarized in the Alaskan Arctic Coast (Arctic Institute of North America, 1974), from which the following information was obtained.

Currents along the Chukchi coast are dominated by a northward flow of water from the Bering Strait. This flow is thought to be maintained by a pressure-induced north sloping sea surface. Several studies have indicated that this flow is uniform in speed and direction from surface to bottom. Russian scientists in 1945 reported average current speeds of 45 cm/sec (0.9 kt) for summer and 10 cm/sec (0.2 kt) for winter. The direction of the primary current is generally parallel to the coast, with eddies and reversals noted in nearshore areas.

Winds have been observed to slow the current, occasionally reversing its direction through the Bering Strait.

3. Tides

Variations in sea level on the Beaufort Shelf are produced by both astronomical and meteorological forces. Astronomic forces, primarily due to the sun and moon, are responsible for the normal tidal fluctuations experienced in large bodies of water. Along the Beaufort Coast, these fluctuations are small with mean ranges of 10 to 30 cm (0.3 - 1.0 ft). Tidal motion is normal to the coast, and the tides occur with semi-diurnal frequency. Because of their small amplitudes, astronomical tides are a minor concern for offshore development.

Deviations in sea level produced by meteorological forces are a significantly greater problem along the Beaufort Shelf. These deviations, known as storm surges or storm tides, are produced by wind stress waves set up by Coriolis forces and barometric pressure differentials acting on the water surface. They are normally associated with storm systems which originate near the Aleutian chain, and which move northward through the Bering Strait. Occasionally, storms moving eastward from the Siberian Shelf produce surges along the Beaufort Coast.

The most severe surges, often accompanied by high waves, occur during September and October when there are large stretches of open water. Winter surges, as late as February, may also occur, but they are normally less severe than during the open water season (Aagaard et al, 1978). Negative surges have also been observed, and appear to be more frequent in winter.

There are no direct measurements of storm surge elevations, but secondary observations of strandlines above the coastal beaches provide evidence of their general magnitude. These studies indicate that positive elevations of 2 to 3m (6.5 to 10 ft) occur occasionally along the Beaufort Coast (Aagaard et al, 1978). Unfortunately, there are insufficient data to develop recurrence intervals for extreme events. Historical records suggest that a 3m (10 ft) surge is relatively rare and might occur only once every 25 to 100 years along parts of the coastline with a westerly exposure.

A few observations of negative surges indicate that they are smaller than positive surges, i.e., on the order of 1m (3 ft) or less. Negative surges are potentially dangerous to ships or other floating vessels in the Arctic because the relatively shallow water provides little draft clearance in many areas.

Along the Chukchi Coast, astronomical tides are reported to be small, averaging about 30 cm (∿1 ft). Storm surge has not been studied in detail. The maximum reported sea level variation is 1.8m (5.8 ft) (Arctic Institute of North America, 1974).

E. GEOLOGY

This section of the report provides a brief overview of geologic features and processes that are of particular interest to Arctic offshore petroleum development. In particular, it examines the nature of sediments and their distribution, subsea permafrost, gas hydrates, and ice gouging. Regional seismicity is also covered. The geographic focus of the discussion is the Alaskan Beaufort Shelf although some information on the Chukchi Shelf geology is also provided.

As is the case with other disciplines, knowledge of the offshore geology of the region is the product of recent scientific investigation. Almost all of the information has been collected within the last ten years as part of a concerted and ongoing effort to understand the Alaskan environment. Within the past five years, this effort has been intensified by the Federal government's OCSEAP work and by numerous petroleum industry studies. Although a great deal has been learned, many of the conclusions drawn have been tentative, since much of the recently collected data have yet to be synthesized. Thus, the information provided in this section represents an interim review which may be subject to substantial revision.

1. Bottom Sediments

The bottom sediments of the shallow shelf areas are of special interest because they represent a possible source of construction materials for the "first generation" of Arctic offshore structures; namely, artificial gravel islands. Coarser substances, ranging from silty sands to gravels, are the most desirable construction materials. Within this range, gravel is the most preferred, although finer materials can be used.

In the Alaskan Beaufort Sea, surface sediments along the shelf are reasonably well mapped except on the inner shelf west of Cape Halkett and east of the Canning River (Barnes and Hopkins, 1978). Figure 1-11 shows the distribution of bottom sediments. These sediments are extremely diverse and range from over-consolidated clays to boulders. The predominant forms are poorly sorted silty clays and sandy muds containing varying amounts of intermixed gravels (Barnes and Hopkins, 1978). In general, coarser sediments are found in the eastern part than in the west. Substantial deposits of sand are available in shallow areas just north and extending east of Prudhoe Bay. Gravel can be found adjacent to the coast from Camden Bay to the Canadian border.

In addition to surface deposits, there is some evidence that coarse-grained (sand and gravel) sediments may be found in substantial quantities beneath areas which are overlain by finer-grained surface deposits. In one study, a series of bore-holes was made between Prudhoe Bay and Reindeer Island to the north. The results are shown as a cross-sectional profile in Figure 1-12. In this area, at least, there appears to be a reasonably abundant supply of gravel at depths beginning 10 to 20m (33 to 66 ft) below the surface.

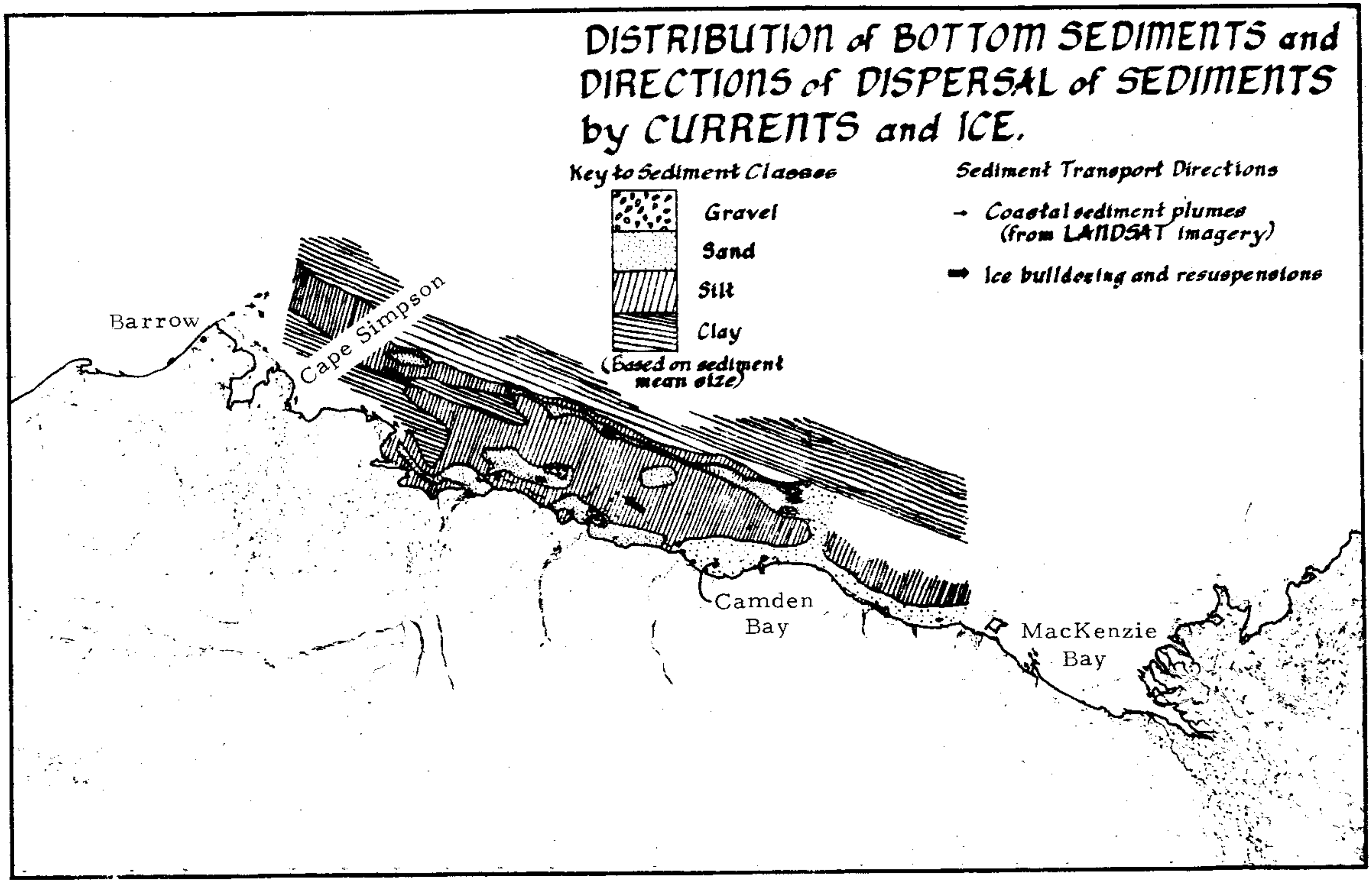


Figure 1-11. Distribution of Bottom Sediments, Alaskan Beaufort Coast (Barnes & Reimnitz, 1974)

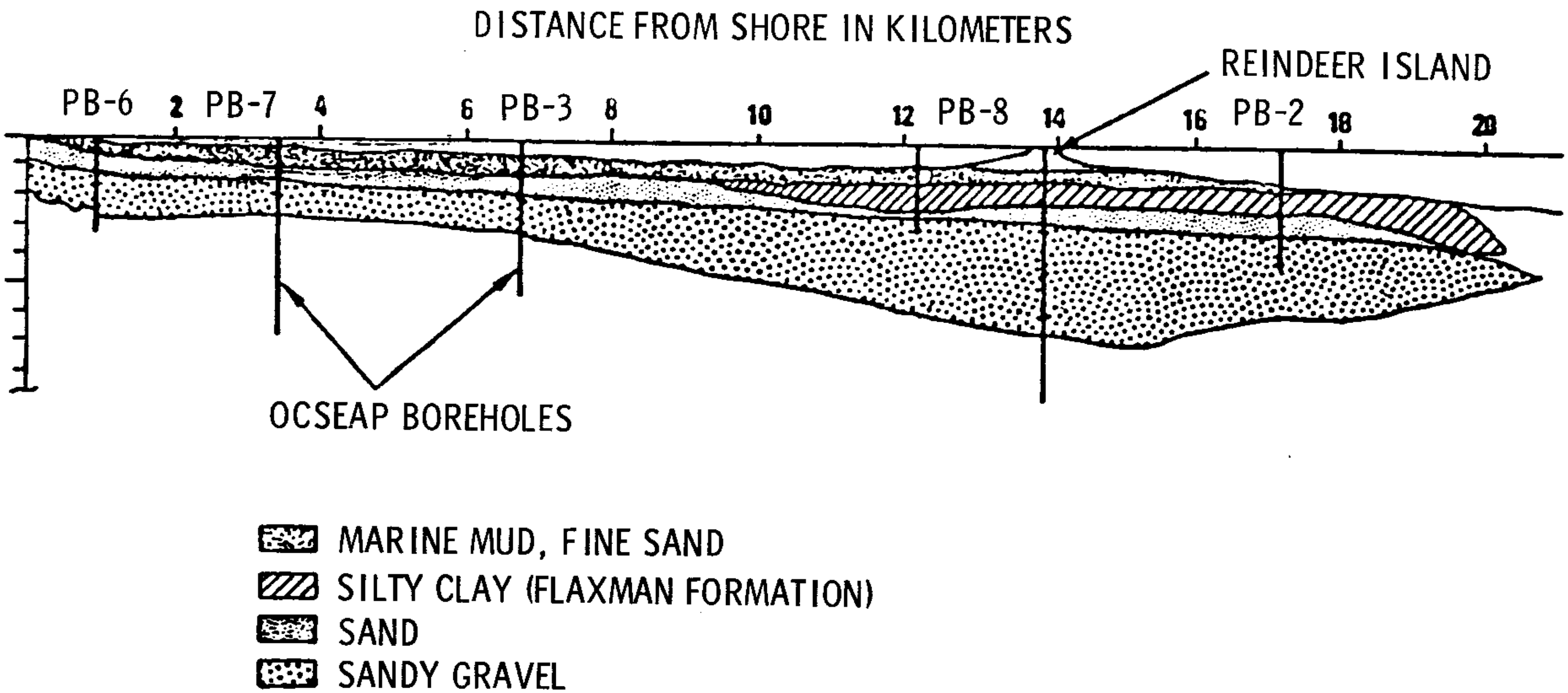


Figure 1-12. Schematic Soil Profile--Prudhoe West Dock to Reindeer Island

The bottom sediment characteristics of the Chukchi Sea have been described by Creager and McManus (1967). They are illustrated in Figure 1-13. In general, these investigators found that grain size decreases away from the shore or downstream from the source of sediment. Coarse gravel is almost always found near cliffs, headlands, or with bedrock outcrops on the seafloor. The only major exception is found in the northeastern Chukchi between Point Lay and Wainwright where gravel was noted offshore but in relatively shallow water. Sand is abundant at many locations inside the 20 to 30m (66 to 100 ft) isobath. Sediments become increasingly finer offshore although clay-sized particles are rare. The sedimentary layer in the Chukchi is relatively thin, seldom exceeding 10m (33 ft) and is often only 3 to 5m (10 to 17 ft) thick.

At present, there are two areas along the Chukchi Coast which are of potential interest for petroleum development. One of these areas lies between Wainwright and Point Barrow. According to the sediment texture map (Figure 1-13), there appears to be an adequate supply of sand-sized particles for potential island construction. The second area lies within Kotzebue Sound. Creager and McManus (1967) report that there are gravel and sand deposits in southern Kotzebue Sound; the northern edge contains generally sandy material. The central portion, however, has various mixtures of silt and clay, or silt and sand. It appears that although sand and gravel are available, they are not found everywhere within the Sound.

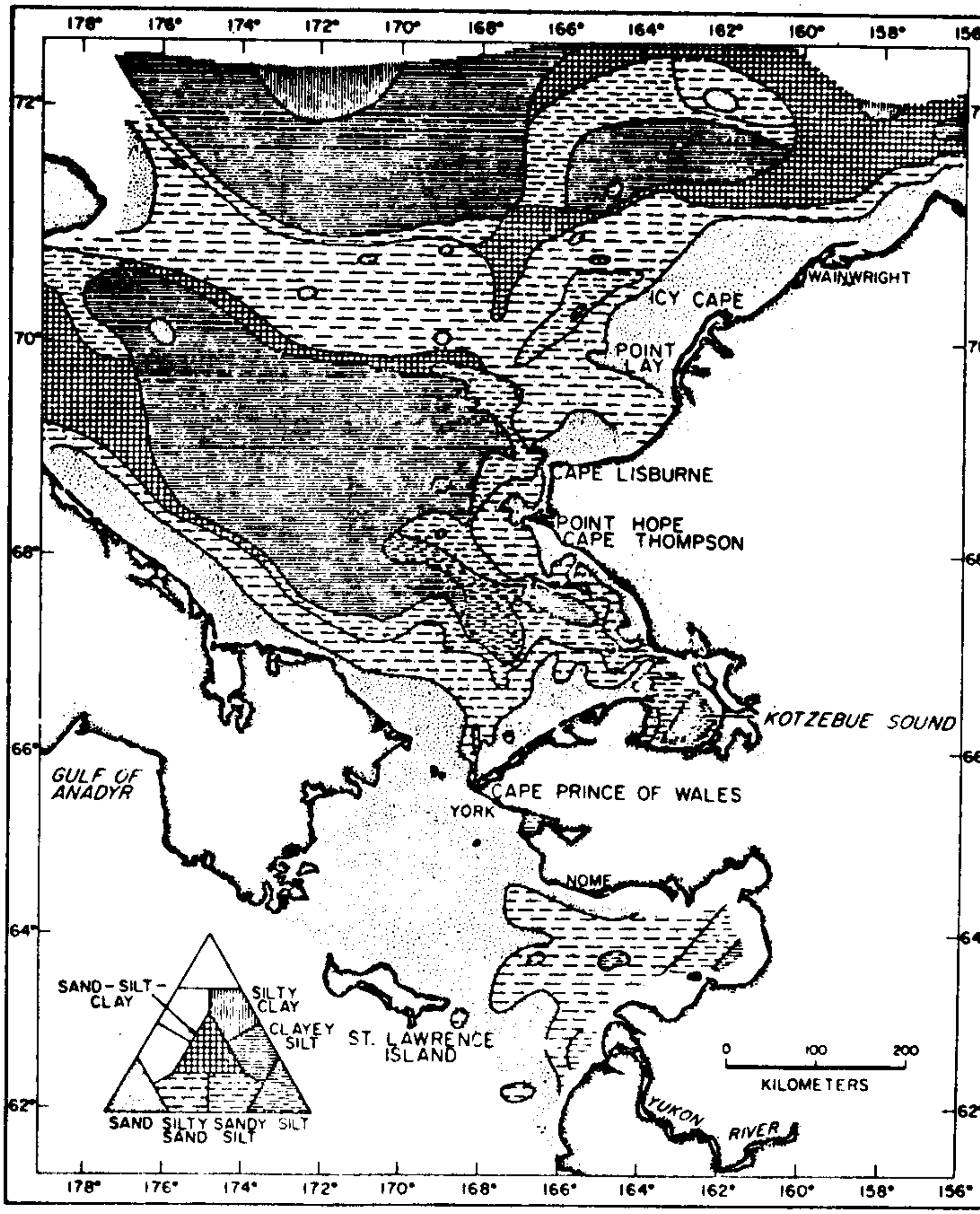


Figure 1-13. Distribution of Bottom Sediments, Chukchi Sea (Creager & McManus, 1967)

2. Subsea Permafrost

Permafrost is defined as "the thermal condition in soil or rock of having temperatures below 0°C (32°F) over at least two consecutive winters and the intervening summer." Beneath the seabed, permafrost may take several forms, ranging from dry cold rock to sediments which contain both ice and a briny liquid phase. From a petroleum development standpoint, permafrost which contains ice is the major concern, because of a drastic change in soil properties when the ice is melted by external heat source. Bottom water temperatures on the Beaufort Shelf are generally below 0°C (32°F) and it is believed that subfreezing temperatures extend well below the seabed (Hopkins, 1977). Recent OCSEAP investigations have shown that ice-bonded permafrost is widely distributed on the Beaufort Shelf, although conditions on the Chukchi Shelf are as yet unknown (Weeks et al, 1978).

The distribution and character of subsea permafrost have been studied by means of boreholes and seismic-refraction methods in the Canadian Mackenzie River Delta, off Prudhoe Bay, and in the Elson Lagoon near Barrow. Each of the three locations has different geological and oceanographic characteristics and histories. It is therefore difficult to draw direct comparisons or to generalize from these observations with a high degree of confidence regarding the whole shelf. There are, nevertheless, some consistent features among the three areas which have led OCSEAP investigators (Barnes and Hopkins, 1978) to a few tentative conclusions which follow:

a. Shallow, inshore areas where ice rests directly on the seabed are underlain at depths of a few meters by ice-bonded permafrost that may extend for a considerable distance. Ice-rich permafrost, and seasonal freezing in an active layer, must be anticipated wherever the water is less than 2m (6.5 ft) deep.

b. Ice-bearing permafrost was once present beneath all parts of the Continental Shelf exposed during the last, low sealevel stand and, consequently, relict ice-bearing permafrost may persist beneath any part of the shelf inshore from the 90m (300 ft) isobath. Observed depths to relict ice-bonded permafrost range from a few meters near the present coast to 250m (825 ft) far off the Canadian coast.

c. Ice-bearing permafrost is probably absent from parts of the Beaufort Sea Shelf seaward from the 90m (300 ft) isobath, although subsea temperatures are probably below 0°C (32°F).

Using these generalizations, OCSEAP investigators have constructed a map (Figure 1-14) showing zones of probable permafrost distribution on the Beaufort Shelf. It is evident from this that any petroleum development which takes place inside of the 20m (66 ft) isobath will probably have to contend with permafrost conditions, especially during drilling operations.

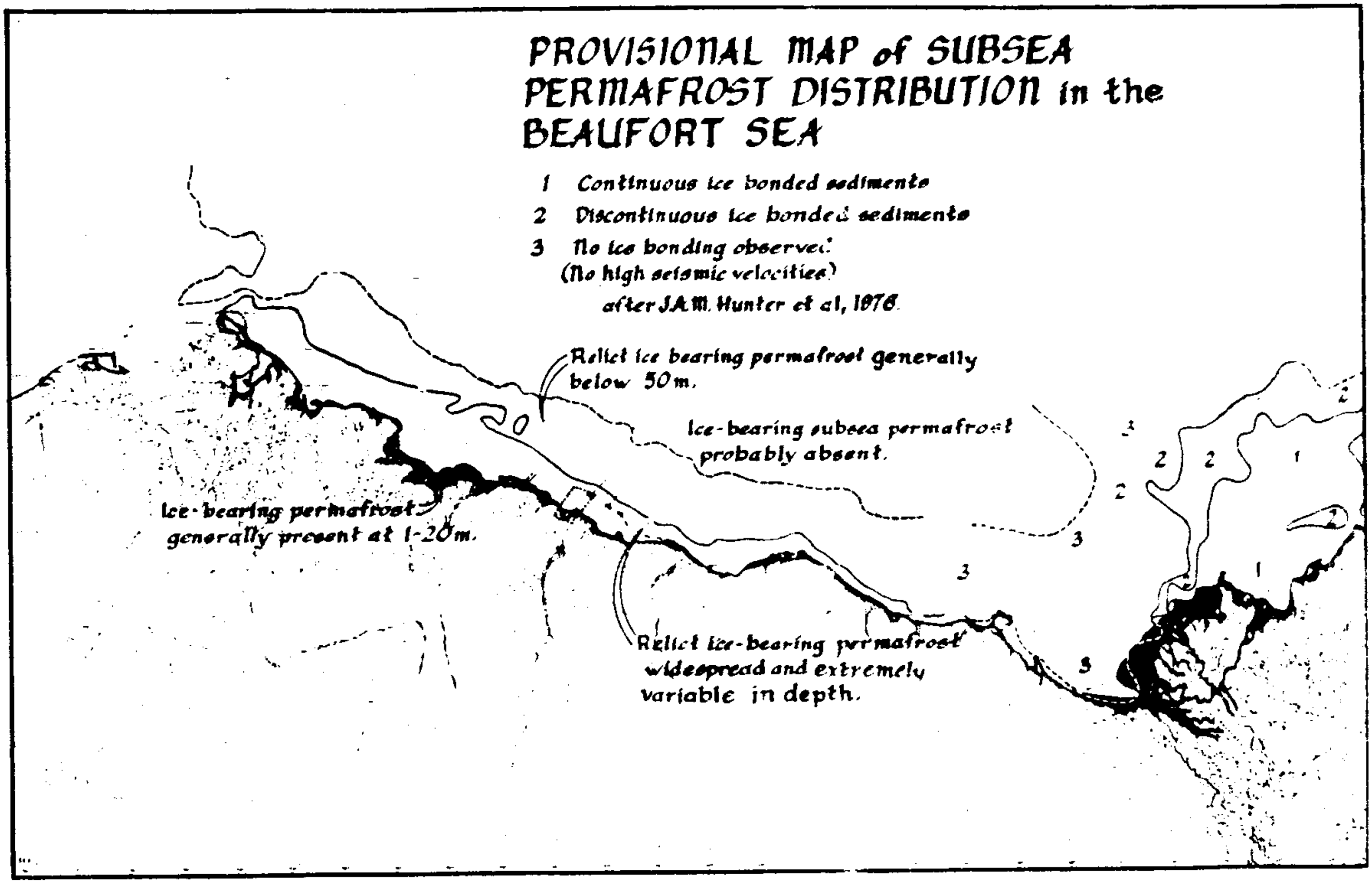


Figure 1-14. Provisional Map of Subsea Permafrost Distribution, Beaufort Sea (Barnes & Hopkins, 1978)

Other major questions as yet unsolved, relating to permafrost distribution, concern the depths below the sea bottom at which permafrost begins, and the thickness of the permafrost layer. Studies done near Prudhoe Bay and the Sagavanirktok Rivers have resulted in profiles shown in Figure 1-15. Near Prudhoe Bay, the permafrost level drops very quickly within a short distance from shore. The Sagavanirktok profile, on the other hand, shows that the permafrost level stays within 50m (165 ft) of the surface at all locations where it is encountered. The thickness of the permafrost layer has not been measured at either location. Based on permafrost depths encountered at nearby onshore locations, theory suggests that permafrost may extend to depths on the order of 500m (1,650 ft) at the Prudhoe Bay location (Barnes and Hopkins, 1978).

3. <u>Frozen Gas Hydrates (Clathrates)</u>

Frozen gas hydrates are a geological feature often encountered either with or beneath ice-bonded permafrost zones. They occur as a latticework of gas and water molecules with a typical ratio of one gas molecule to six water molecules. In the frozen crystalline state, these hydrates exhibit no inherent pressures normally associated with gases in the fluid state. If they are heated, the frozen hydrate may decompose into either gas and ice or gas and water. The gas which is released has a much greater volume and/or pressure than it had in the frozen state. One cubic foot of saturated hydrate can

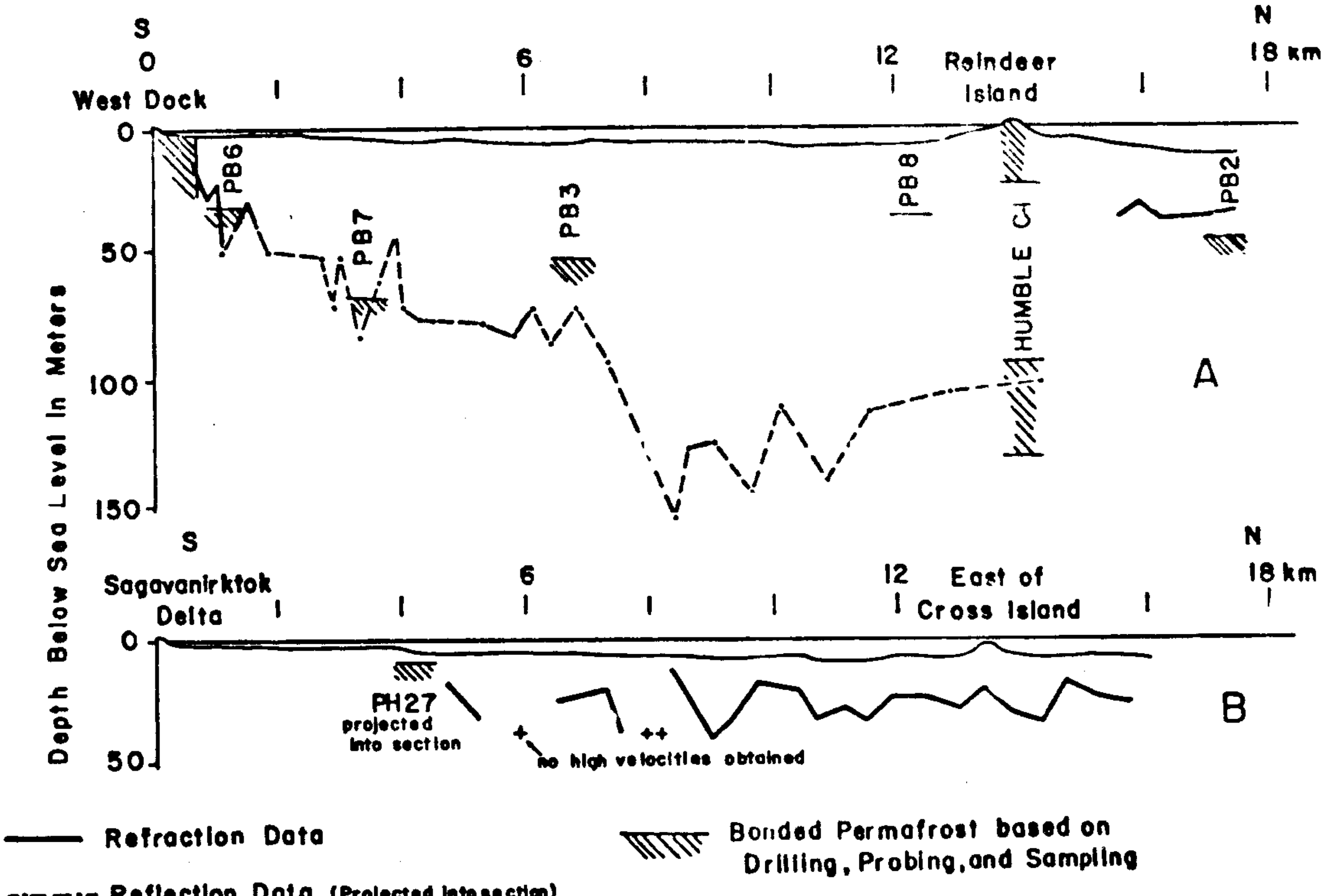


Figure 1-15. Subsea Permafrost Data Offshore From Prudhoe Bay and the Sagavanirktok River
(Barnes & Hopkins, 1978)

produce 160 standard cubic feet of natural gas. Because of the high pressures which may result from thawing, frozen hydrates are of obvious concern to offshore drilling operations.

Unfortunately, very little is known about the distributions of frozen gas hydrates in offshore areas. They have been encountered in parts of the Canadian Beaufort, Mackenzie Delta and in the Canadian Arctic Islands. Onshore studies of frozen hydrates show that they are vertically limited to depths of about 200 to 1,500m (660 to 5,000 ft) (Hunter et al, 1976).

There is indirect evidence that frozen gas hydrates, or trapped gas, may have widespread distribution along the Alaskan Beaufort Sea. Seismic reflection records from many areas of the inner shelf show intermittent patches of acoustic energy loss which, in other regions, have been found to be positively-correlated with the presence of gas-charged sediments (Weeks et al, 1978). In deeper water, Grantz et al (1975) found an unusually strong seismic reflector which mimicked the seafloor at depths of 100 to 300m (330 to 1,000 ft) below it. This phenomenon occurred only where water depths exceeded 400 to 600m (1,300 to 2,000 ft). Grantz et al (1975) have postulated that this reflector represents a cap of frozen gas hydrates and sediment which acts as a structural trap for free hydrocarbon gases below it.

4. Ice Scour

Ice scour, also referred to as ice gouging, is a phenomenon caused by sea ice moving in contact with bottom sediments. Ice scour is typically manifested as a linear or curvilinear depression with flanking ridges of displaced seabed materials (Figure 1-16). Scour marks may occur as solitary features or in groups. Ice scour may be caused by any type of ice with sufficient draft and momentum to penetrate the seafloor. Pressure ridges are probably the most common type of ice feature to produce major depressions in the seafloor, although ice islands and their fragments are capable of scour as well.

Reimnitz and Barnes (1974) have conducted numerous studies of ice scour on the Alaskan Beaufort Shelf. Scour densities, depths of incision, and dominant trends are reasonably well known in the region between Cape Halkett and Flaxman Island inside the 15m (50 ft) isobath (Figure 1-17). However, such information is lacking in deep water areas and in the eastern and westernmost sectors.

Reimnitz and Barnes (1974) findings include the following observations: Ice-scoured relief tends to dominate the small-scale shelf morphology between depths of 8 to 10m (26 to 33 ft) out to at least 75m (250 ft). Ice scour marks have been observed at depths exceeding 100m (330 ft). The greatest intensity of scouring corresponds to depths where the zone of grounded ridges (Stamukhi zone) is formed in 10 to 20m (33 to 66 ft) of water. Localized areas of intense scour are also

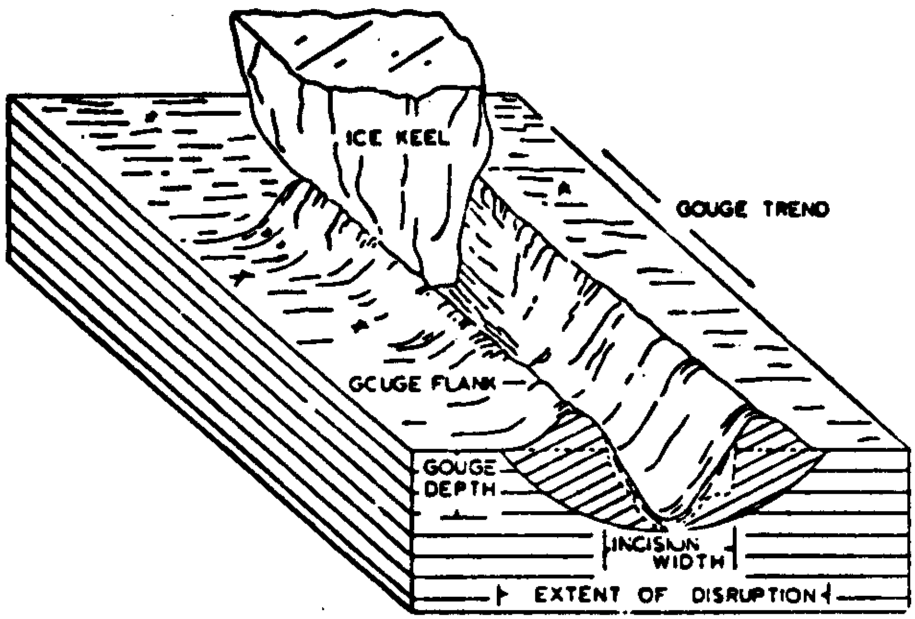


Figure 1-16. Profile of Idealized Ice Scour (Barnes & Hopkins, 1978)

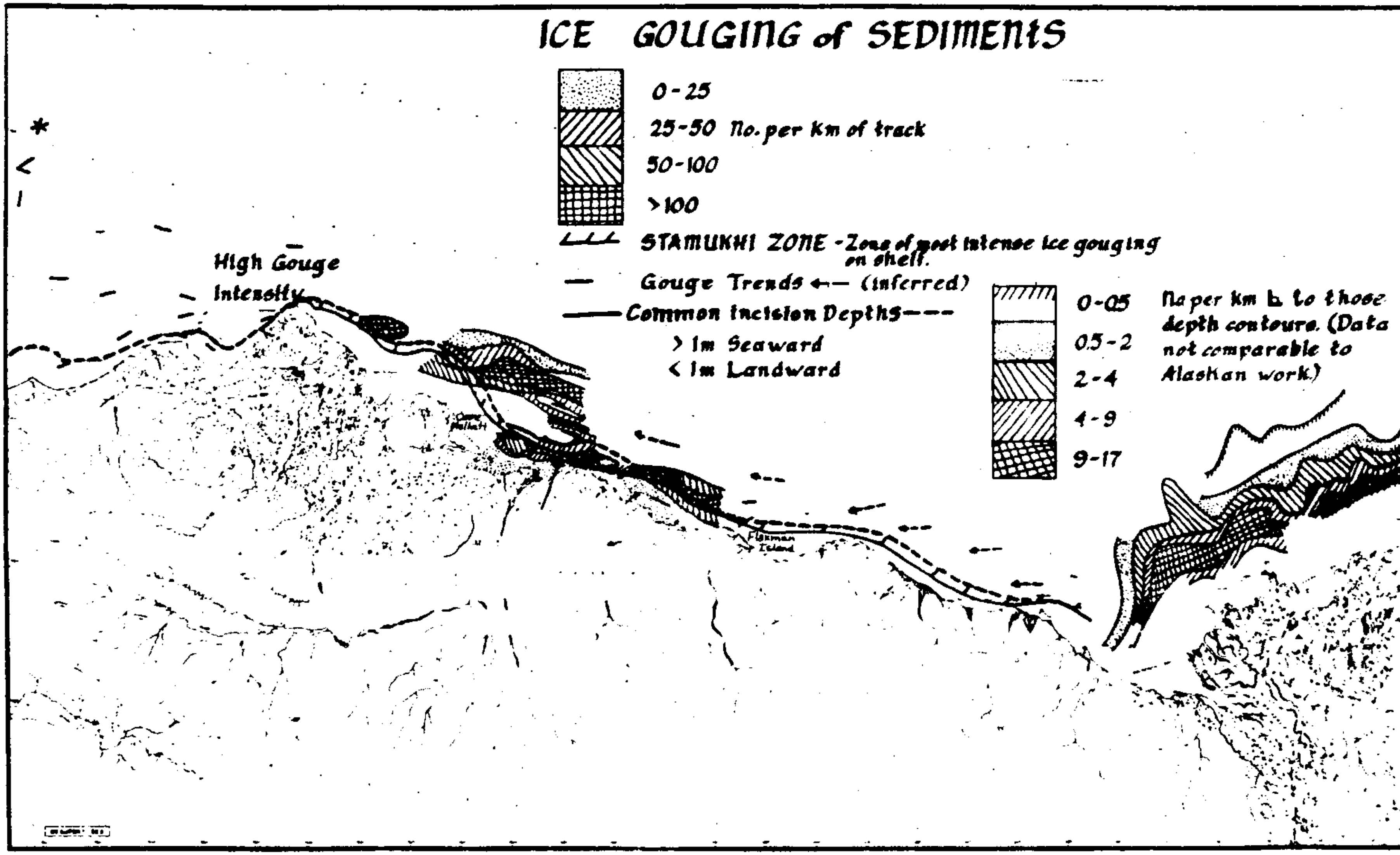


Figure 1-17. Beaufort Sea Ice Scour (Barnes & Hopkins, 1978)

found on the seaward side of shoals. The density of scour marks varies from nearly zero to over 100 per km (60 mi). The lowest values occur in the shelter of barrier islands, off major river deltas, and on the shoreward side of bathymetric highs. Scour depressions show a preferred east-west orientation, parallel to the Beaufort Coast at most locations. Scour depths are commonly less than 1m inside the zone of grounded ridges. Beyond that zone, scour depths may be much greater. The observed extreme on the Alaskan Beaufort Coast is 5.5m (18 ft) in a water depth of 38m (125 ft). In the Canadian sector, a 6.5m (22 ft) scour was reported in 40 to 50m (130 to 165 ft) of water (Lewis, 1977). Table 1-10 summarizes ice scour characteristics in the Alaskan Beaufort Sea.

Toimil (1978) has performed a reconnaissance study of ice scour in the eastern Chukchi Sea. The following observations were noted: the density of ice scour increases with increasing latitude, increasing slope gradients, and decreasing water depth; scour was observed to occur at least as far south as Cape Prince of Wales; densities of over 200 gouges per km (320 per mi) were encountered in water depths less than 30m (100 ft); no values higher than 50 per km (80 per mi) were found in water depths deepther than 50m (165 ft); the maximum depth at which evidence of scour was observed was 58m (192 ft) and maximum incision depths were found in water depths of 36 to 50m (120 to 165 ft); an extreme incision depth of 4.5m

Table 1-10. Ice Scour Zones in the Alaskan Beaufort Sea (Kovacs, 1972)

REGION	WATER DEPTH (M)	TYPICAL SCOUR DEPTH (M)	MAXIMUM SCOUR DEPTH (M)	FREQUENCY OF SCOUR TRACKS
COASTAL SHELF	0-7	< 0.5	NO DATA	VERY FREQUENT
MID-SHELF	7-30	< 1.5	3-4	10-15/KM
OUTER SHELF	30-80	NO DATA	10	SLIGHT BEYOND 45 METER DEPTH

(15 ft) was encountered at a depth of 35 to 40m (115 to 130 ft).

Toimil (1978) also noted the following differences between scour in the Beaufort and Chukchi Seas: in the Chukchi, scour densities are variable and patchy under otherwise uniform conditions; gouge trends in the Beaufort show a preferred orientation, but this feature is poorly developed in the Chukchi; in the Chukchi, ice scour is associated with, and may be modified by, strong currents; the maximum water depth of ice scour occurrence appears to be shallower in the Chukchi Sea than in the Beaufort.

5. Seismicity

Most parts of the Arctic coastal plain and the continental shelf of the Beaufort Sea are aseismic, except for a limited zone which extends offshore near Barter Island (Barnes and Hopkins, 1978). Seismograph studies begun in 1975 by the University of Alaska show that this zone is a continuation of the earthquake belt which arcs through the Aleutian Islands along the south shore of Alaska and then turns northward through Cook Inlet and central Alaska (Figure 1-18).

In spite of a fairly limited data base, several characteristics of the region's seismicity are known. All of the earthquakes recorded thus far have been shallow. Offshore focal depths have been less than 25 km (16 mi), and those on the adjacent coastal plain have been less than 50 km (30 mi).

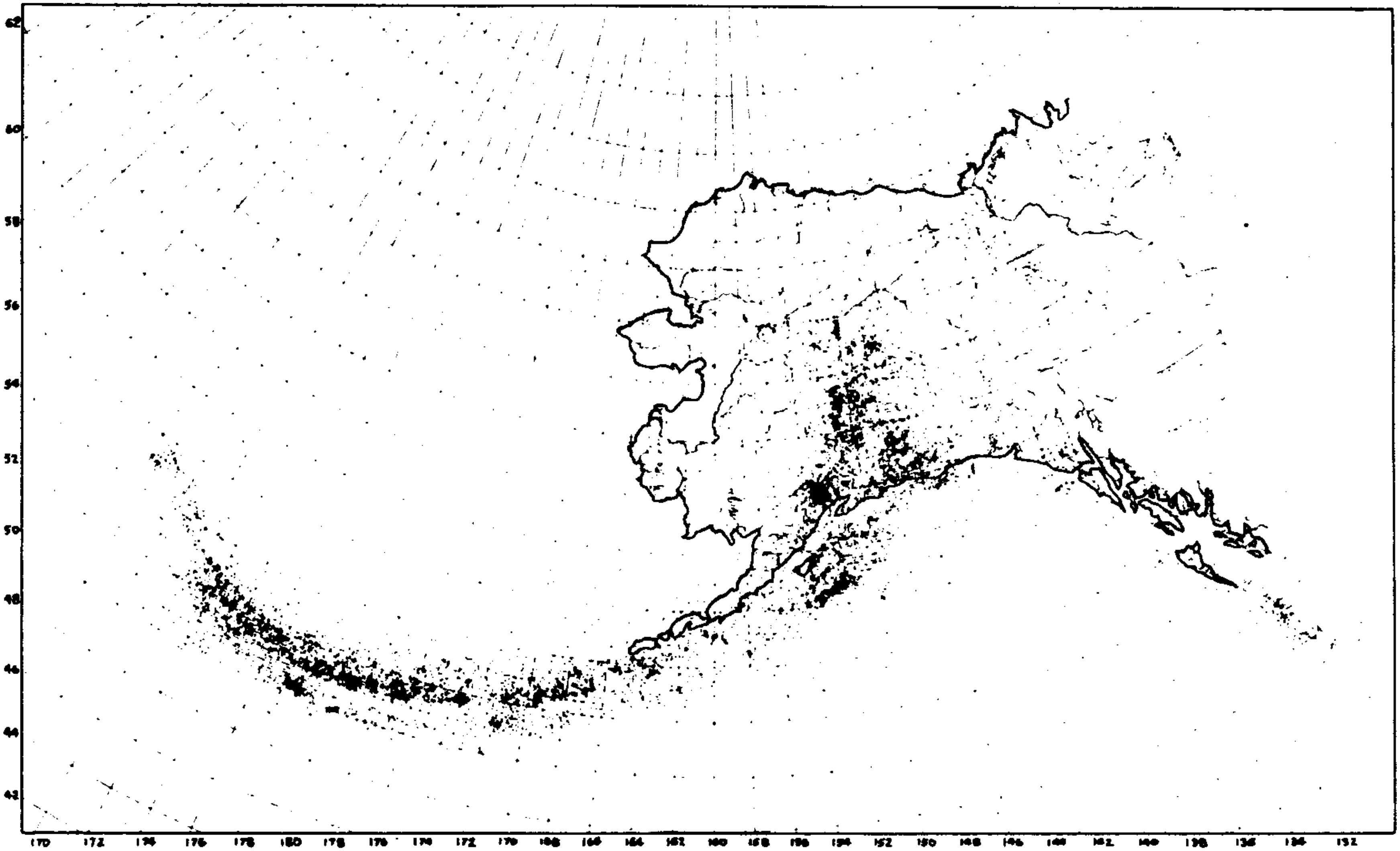
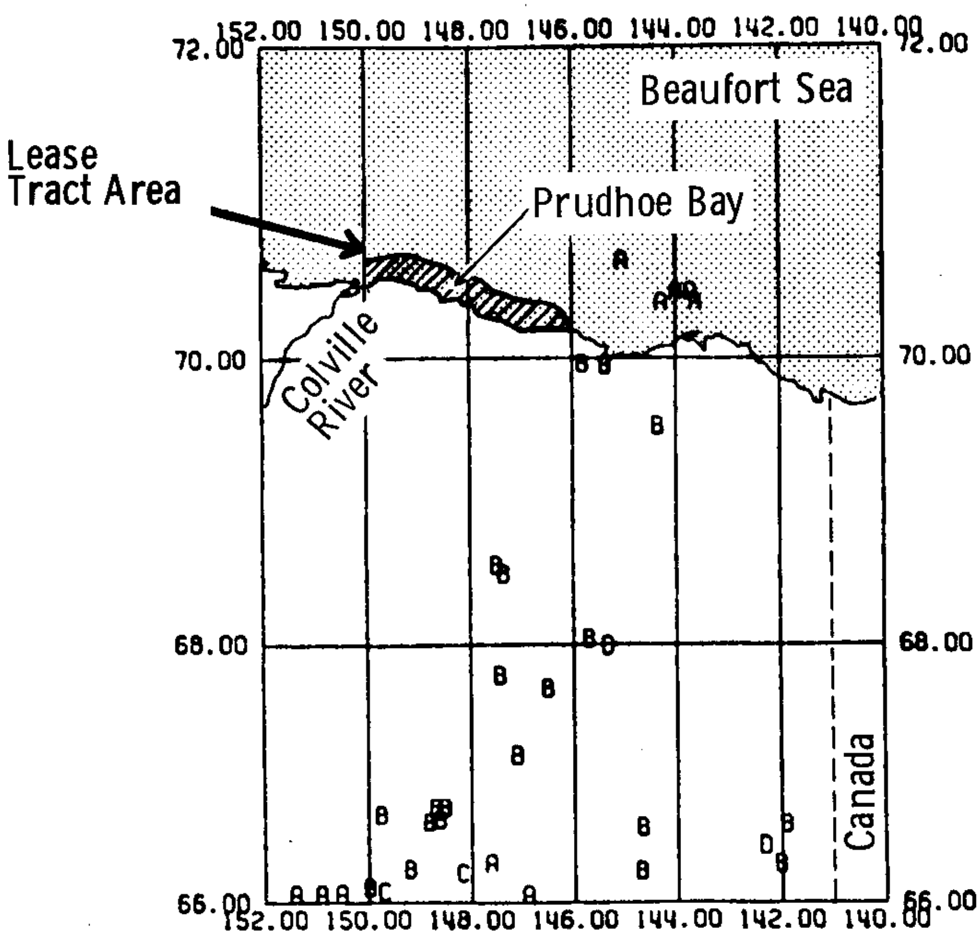


Figure 1-18. Earthquakes In and Near Alaska (Through 1974) (Barnes & Hopkins, 1978)

Figure 1-19 shows the location and focal depths of earthquakes in northeastern Alaska. The largest earthquake (M_L = 5.3), recorded within the last ten years occurred about 30 km (20 mi) offshore from Barter Island. Aftershocks from this quake indicate the presence of an ENE-WSW seismic trend along axial traces of the offshore folded structures (Barnes et al, 1978). Other earthquakes recorded in northeastern Alaska have all had magnitudes smaller than 5.0.

A recent study prepared for the Alaska Subarctic Offshore Committee by Woodward-Clyde Consultants (1978) examined potential ground motion characteristics that might be associated with earthquakes in the Beaufort Basin and southern Chukchi Sea (Hope Basin) areas. Assuming a random earthquake source in each area and a seismic event with a 100-year return period of magnitude 6.5, Woodward-Clyde (1978) computed various ground motion parameters and their associated return periods. It was found that ground accelerations of 0.05 g and 0.03-0.12 g could be expected to occur, in the Beaufort and Hope Basins respectively, on an average of once every hundred years. The associated maximum velocities were approximately 3.1 cm/sec (1.2 kt) in the Beaufort, and 2.2 to 9.0 cm/sec (0.9 to 3.6 kt) in the Hope Basin. However, Woodward-Clyde consultants warn that the analysis is very sensitive to the seismicity level. If a larger magnitude earthquake were to occur, the accelerations and velocities would be significantly increased.



A = Focal depth 0 to 25 km
B = Focal depth 25 to 50 km
C Focal depth 50 to 75 km
D - Focal depth 75 to 100 km

Figure 1-19. Locations of Northeastern Alaska Earthquakes (Prior to 1975) (Hopkins, 1977)

F. ENVIRONMENTAL HAZARDS

Foregoing sections of the report have provided an overview of the environmental characteristics which are of concern for offshore development in Arctic Alaska. A number of the environmental parameters discussed pose difficulties or hazards for offshore work. Some of these hazards relate to operations, such as drilling or logistics. Other hazards are more important to the design of structures and equipment. Because of the uniqueness of the Arctic environment, it is appropriate to review the difficulties which might be encountered.

It should be noted that many of the problems discussed are site specific and may not be found at all locations. Furthermore, the problems are not unique to the Alaskan Arctic, and some have been dealt with by industry in other Arctic areas such as the Mackenzie Delta.

1. Location

Remoteness and inaccessibility are fundamental characteristics of the Alaskan Arctic. In combination with the severe climate, these factors pose formidable difficulties for logistics of any type. Both the Beaufort and Chukchi coasts are many hundreds of miles from major industrial and supply centers, and access routes are few and limited. Normal supply efforts will require exceptional planning and scheduling such as was done in the Prudhoe Bay development.

2. Ice

The presence of ice in some form in all but a few months of the year is the single greatest environmental hazard posed by the offshore Arctic. Because of the potentially great forces which ice may exert, the relative importance of other environmental concerns is decreased. The problems posed by ice are manifold. For purposes of clarity and organization, it is useful, therefore, to discuss ice in terms of its natural zonation because each zone poses somewhat different problems for development. The summer open water period is also considered since it represents a seasonal zone of variable duration and extent.

a. Bottom-Fast Ice

This zone includes an area of fairly smooth, stable ice of predictable strength and dimension. It is considered the safest zone in which to operate with current technology. The primary hazards are considered to be large motions which can occur in the ice during fall freeze-up and spring break-up. Such motions can occur quickly with little warning. The problem is mitigated somewhat by the fact that ice motion normally occurs when the ice is thin or weakened by melting. Nevertheless any structure contemplated for this zone must withstand sheet ice pressure or accommodate the ice motion. Even during the winter months, some ice motion is possible. Instances of ice override, previously described in the text, indicate that large sheets of ice may be broken from the main fast ice sheet and move considerable distances when driven by the wind.

b. Floating-Fast Ice

This zone begins at the edge of the bottom-fast ice and continues seaward to the 15 to 20m (50 to 66 ft) isobath. The offshore barrier islands are found within this zone. The major hazard within the floating-fast ice is ice movement. Unlike the bottom-fast ice zone, motion normally occurs in winter. Inside the barrier islands, movements of a few meters during the winter season can occur. Seaward of the islands, larger seasonal movements up to 1 km (0.6 mi) have been observed (Weeks and Kovacs, 1979). In both cases, ice movement is unpredictable and may develop relatively rapid, even in a matter of hours.

An additional hazard, which occurs much more frequently outside of the islands than inside, is the presence of large (up to several hundred meters in diameter) multi-year floes. These floes are embedded in the fast ice and are stronger than the surrounding first-year ice. The hazards connected with any type of exposed structure in this zone are obvious. They should be protected against significantly greater ice forces than in the bottom-fast ice zone.

It is likely that surface transport would be used for winter logistic support for structures located within both bottom-fast and floating-fast ice. Ice surface transport may entail the use of large, heavy vehicles requiring thick ice to support them. Two operational problems are encountered with this type of transport: the first is verifying the thickness of ice along a proposed route; the second is detecting cracks or leads in the ice which occur as a result of differential movements (Weeks, 1978).

Ice thickness may be determined by direct drilling, a tedious process, or by a pulsed radar system which is still an experimental tool. Detecting cracks is somewhat more difficult since they tend to refreeze quickly and become covered with drifting snow. If the ice is insufficiently thick, moving vehicles may break through and become trapped. In darkness or in blowing snow, travel over ice containing cracks may be perilous. An accident caused by this exact situation almost cost two men their lives in March, 1979, at a site north of Prudhoe Bay (Weeks, personal comment).

c. Pack Ice

In this discussion, the pack ice zone includes the zone of grounded ridges, the floating extension, and the drifting pack ice. Year-round development and operation within the pack ice presents formidable difficulties. The principle hazards to structures in the zone are ice movements, which may exceed 1 km per day, and encounters with such massive ice features as multi-year ridges, floebergs, or ice islands.

The zone of grounded ridges is an area of intense interaction, especially during its initial formation in early winter. There is constant shearing and crushing motion between the fast ice and the drilling pack. Large pressure ridges, tens of meters thick, may be formed and become grounded. With time, the ridges may achieve greater strength through melting and refreezing. Occasionally ridges pose a danger when they become ungrounded in the summer, and drift along the coast. There are some areas on the Beaufort Shelf where elongated systems of shear ridges form in which large ridges are arrayed, one after another, like furrows in a plowed field (Weeks, 1978). Such systems may extend for tens of kilometers. A drifting ungrounded portion of such a system can be massive and hazardous to any structure in its path.

Any type of surface travel or transport within the pack ice zone is extremely hazardous and difficult. In contrast to the fast ice, which is relatively smooth, the pack ice has numerous deformations and major ice features embedded in it. It is subject to large, unpredictable movements which create wide leads, especially in early winter and late spring. Aircraft, and perhaps air cushion vehicles, are the most likely form of transportation.

d. Open Water

The open water zone is a summer phenomenon of extremely variable duration and extent. It is vital to the conventional marine transportation system which resupplies much of the North Slope during the summer season. In the future, petroleum development equipment, supplies, and even offshore structures may be transported on barges or ships to the Arctic. Conventional drillships, if they are used, will probably operate during this season. Furthermore, it is likely that much of the offshore marine construction required for petroleum development will take place in open water.

The major problems in this zone are predicting the severity of ice conditions during the summer season and forecasting the temporary movements of pack ice toward the coast. The first problem has been studied by Rogers (1978) who has developed a method of correlating the severity of ice conditions with temperatures which occur during the spring months. This method, which appears to have some promise for predicting summer ice conditions, may be very useful for planning summer operations.

The problem of forecasting pack ice encroachments is less tractable. Southerly pack ice movement caused by storm winds may bring the pack into shallow water in a matter of hours. Prior knowledge of such movement is especially desirable for operating drillships, marine traffic, and other offshore activities such as construction which may be endangered by sudden shifts in the pack. Various predictive schemes exist for forecasting pack ice motion, but none have been reliably verified (Weeks, 1978). Furthermore, there are no real-time remote sensing systems which are available to provide an early warning of pack ice shifts.

e. Other Concerns

There are several other ice-related concerns which can occur at any location where moving ice is present. They tend to be less severe in the bottom-fast ice zone and in the floating-fast ice zone which is protected by barrier islands. Each is discussed in the following:

(1) Ice-Induced Vibrations. Ice-induced vibrations could be generated by a contact of rigid structures or structural members with moving ice. At least one platform in Cook Inlet, Alaska, suffered fatigue failures which were attributed to excessive vibrations caused by ice. The platforms affected by this problem were specially-designed caisson-legged structures. It is doubtful that this type of platform would be used in the Beaufort or Chukchi Sea. Nevertheless, the phenomenon of the ice-induced vibrations may be of concern when designing foundations, structures, vessels or machinery.

(2) Erosion. Ice-caused erosion may manifest itself in several ways. Structures such as artificial islands which are made from fill materials may be subject to foundation erosion by moving ice. In the Canadian Mackenzie Delta region, various protection measures have been developed to protect islands from erosion by ice and waves.

On a smaller scale, ice may abrade and consequently erode more rigid structural materials such as steel, concrete, or rock. A related problem, corrosion/erosion, may result in the rapid decomposition of iron or steel. Corrosion is enhanced by the high oxygen content of cold Arctic waters. Oxidized materials, which normally form a semi-protective coating, are removed by ice abrasion, constantly exposing new metal to corrosive action (Weeks, 1978).

(3) Ice Scour. Ice scour is a potentially serious problem for equipment located at or below the seabed. Such equipment might include pipelines, blowout preventer stacks and subsea production systems. Protection for seafloor devices must be provided. Two design solutions studied by industry are burying such devices below the maximum probable scour depth; and providing a shield or armor, around them. The present problem with the burial strategy is that it is difficult to determine a safe depth without overdesigning. In the Alaskan Beaufort, for example, the maximum scour depth yet encountered is 5.5m (18 ft) in 35m (114 ft) of water. It is not clear whether this scour was formed recently, or at some time in the past, when the sea level was much lower. However, it is difficult to assess the probability of such an event. Presumably, it is sufficiently rare so that burying a pipeline in excess of 5.5m (18 ft) could represent a significant overdesign unless such deeper burial can be economically achieved. The problem

is compounded by the fact that scour depths vary with water depth, slope angles, bottom sediments, and other factors. The ultimate solution may well be that specific detailed site studies will be required for each situation where burial is required.

There are similar difficulties in designing a protective shield around seabed equipment. The shield should be constructed to withstand the impact of drifting pressure ridges whose size is difficult to predict.

3. Climatic Hazards

Although ice is clearly the primary challenge with respect to engineering and design in the offshore Arctic, weather and climate pose difficult operational constraints. A brief enumeration of these concerns follows.

a. Temperature

The sub-zero air temperatures which prevail most of the year create extremely inhospitable outdoor working conditions. In the winter it is necessary to wear layers of bulky clothing which reduce work efficiency and often obscure lateral vision. Wind chill severely compounds the low temperature effect. Machinery, which must operate in low winter temperatures, is frequently temperamental and certain materials are subject to brittle fracture. Low water temperatures are an obvious human hazard at any time of year. Survival times are short and rescue efforts may be difficult. However, experience obtained at Prudhoe Bay and even in the Cook Inlet has allowed the development of techniques and precautions for minimizing exposure to these hazards.

b. Wind

Persistent and moderately strong winds contribute to low temperature problems through windchill effects and also impair visibility by blowing snow and creating blizzard-like conditions. Occasional hurricane-force winds, in summer and fall, are a design consideration for offshore structures as they create high waves and storm surges.

c. Superstructure Icing

Superstructure icing may be a problem during fall months when there is sufficient wind to create sea spray, and the temperatures are low enough to freeze it. Although most permanent structures would not be significantly affected by icing, vessels having a high center of gravity, such as drillships or crane barges, could be vulnerable.

d. Low Visibility/Optical Phenomena

Periods of impaired visibility due to darkness, fog, blowing snow, whiteout, etc., are common in the Arctic. These pose difficulties for logistics, particularly flying and over-ice surface travel. An important concern is the ability to detect and track oil spills which may occur during the winter darkness.

e. Weather Forecasting

Reliable weather forecasting is vital during the summer transit and construction season. It is also necessary in winter for planning logistics. However, present standards for Arctic forecasting are relatively poor in comparison with temperate regions. This is due to a paucity of historical data, and a lack of reporting stations, especially offshore. Furthermore, remote sensing systems capable of obtaining high resolution data under conditions of clouds and darkness, have not been deployed in operational weather satellites (Weeks, 1978).

4. Geological Hazards

Potential geological hazards include bonded permafrost, gas hydrates, coastal erosion, and seismicity. The severity of each hazard may vary greatly as a function of location.

a. Permafrost

The presence of permafrost is an important consideration in the design and construction of offshore structures and pipelines. If offshore permafrost is disturbed by heating, ice within the permafrost will melt, and this can result in subsidence of the surrounding sediment. If permafrost is close to the surface, structure foundations may need to be insulated or refrigerated to protect the permafrost. Pipelines containing hot oil may also require insulation or refrigeration. These precautions are standard practice on the North Slope. In offshore locations, protection of permafrost is especially important due to the difficulty of making repairs, and because subsea permafrost usually exists at warmer temperatures (in combination with varying salinity content). Hence, it is disturbed more easily than terrestrial permafrost (Barnes and Hopkins, 1978).

Permafrost can also pose difficulties during drilling and production operations. Hot drilling muds and oil are capable of thawing permafrost around the well bore. If the permafrost should subsequently refreeze (freeze-back), the resulting pressure could damage the casing. This problem was encountered on the North Slope and in the Canadian Arctic. It has largely been solved through proper well bore and casing design and through changes in drilling procedures.

b. Gas Hydrates

Gas hydrates are a problem which has not been fully evaluated at the present time. They are capable of reducing the mud weight in the well during drilling as a result of the heating and decomposition of the hydrate. If the change in well pressure is not noted or if it cannot be controlled, a damage to the well head may result. At least one blowout in Canadian Arctic exploratory wells has been attributed to hydrates (Pinlott, 1976).

A perplexing problem related to hydrates is detection prior to drilling. Short of a direct encounter, there is no positive method for locating them. Indirect evidence, discussed previously, suggests that they may be widespread on the Beaufort Shelf.

c. Coastal Erosion

Oceanographic origin and ice erosion of the beaches and bluffs along the coast is not a hazard, per se, but may be an important consideration in the design and construction of pipelines which must make coastal crossings. Erosion rates are very rapid along the Beaufort coast, averaging 1 to 5m (3 to 16 ft) annually. In an extreme case, a high bluff retreated 60m (192 ft) during a single storm (Barnes and Hopkins, 1978). Landfalls of submarine pipelines must therefore be sited appropriately to minimize the hazard of exposure. It is also worth noting that onshore facilities, such as camps and staging areas which may be used for many years, must also be located a safe distance inland.

d. Seismicity

Present evidence indicates that the Arctic coastal areas have low seismicity with the exception of one seismically-active zone near Barter Island. This area lies to the east of the first-proposed Beaufort lease sale tracts. Recent seismic records for this location show that earthquakes of magnitudes 1 to 4 have occurred in the past several years. It is believed that the potential for an earthquake of magnitude 6 exists (Weeks et al, 1978). If such an earthquake did occur, nearby lease tracts may experience some motion but probably not enough to do serious damage.

Further evaluation of this hazard may be required. The seismic history is presently too short for a definitive assessment of the potential seismicity. Faults are not well mapped and there is insufficient data for precise determination of the ground motions associated with a possible earthquake in that area.

5. Oceanographic Hazards

Oceanographic phenomena including waves, currents, and storm surges are largely design considerations for offshore structures. They constitute hazards only to the extent that they are unknown. Relatively simple engineering solutions are available to deal with them if reasonable estimates of their magnitudes can be obtained.

a. Waves

Waves are a less serious concern in the Arctic than in temperate areas because they are generally smaller and occur only during one to three months of the year. The principal concern from waves is their potential for overtopping structures and their erosive properties. Artificial fill islands are especially vulnerable because of their construction material and normally low freeboard. Erosion may be a substantial problem in island construction if the island is not properly designed. Storm waves are capable of leveling an unprotected island within a matter of days. The danger from wave overtopping is the risk of inundation of drilling equipment and supplies. There is additional hazard to human life, if such an event were to occur suddenly, without warning. Consequently, various designs have been developed by offshore operators in the Canadian Arctic to prevent this from happening. They are discussed in Section II.

b. Currents

A knowledge of currents is required to assess the potential for scour around the foundations of bottom-founded structures. Present information, although meager, suggests that the general magnitude of normal currents is quite low and that scour should not be a major problem. However, additional information is needed for both storm-generated currents and for currents beneath ice. It is probable that high currents are associated with large storm surges known to occur in the region.

c. Storm Surge

Storm surges pose a number of risks for offshore structures. Similar to waves, they are capable of inundating structures having insufficient freeboard. It is also likely that severe surges may be accompanied by high waves since they tend to occur near the end of the open-water season when there is maximum fetch between the land and pack ice. Since surges are wind drive, they may also be accompanied by fragments of floating ice. However, such fragments should be small, and should not present a serious structural design problem. Thus, beside the hazard of inundation by waves and surge, there may be an additional danger of being overridden by ice. This is clearly a much more serious problem.

Winter surges, although less frequent and severe, may cause movement in otherwise stable ice. Winter surges up to 1.4m (4.5 ft) have been observed on the Beaufort coast. Structures which may be sensitive to sudden ice motion such as grounded barges or artificial ice islands, could be adversely affected (Weeks et al, 1978).

6. Summary

A brief summary of the principal development hazards is shown in Table 1-11.

Table 1-11. Environmental Hazards

ICE - RELATED HAZARDS	POTENTIAL CONSEQUENCES
• Bottom Fast Ice	• Movement normally small but can be large during freeze or breakup; may imperil floating structures or unprotected risers.
• Ice Override	• Poorly understood phenomena. Potential for overtopping artificial islands.
• Floating Fast Ice	• Motion over 1000 meters per winter season. May overtop artificial islands or create large lateral forces.
• Cracks and Thin Ice	• Difficult to observe or predict. Hazard to personnel and surface transport vehicles.
• Open Water	• Unpredictable invasions of pack ice possible in all unprotected areas.
• Ice-Induced Vibrations	• May cause fatigue failures in rigid structures.
• Ice-Induced Erosion	• Loss of foundation materials.
• Ice Scour	• Possible damage to subbottom structures or equipment such as wellheads, BOP stacks, pipelines or subsea production systems.
• Pack Ice	• Enormous forces against structures may be created by pressure ridges, floebergs, or ice islands.

Table 1-11 (cont'd). Environmental Hazards

OTHER CLIMATIC HAZARDS	POTENTIAL CONSEQUENCES
• Low Temperatures	• Serious reduction in personnel efficiency. • Brittle fracture of unsuitable construction material.
• Wind	• Moderately high velocities possible. • Wind loads must be accounted for in structural design. • Contributes to low temperature effects - "Wind Chill"
• Superstructure Icing	• Potential hazard for floating drill ships in summer and fall months.
• Low Visibility/Optical Phenomena	• Periods of impaired visibility due to darkness, fog, haze, whiteout etc., greater in Arctic than in temperate zones. • Potential adverse impact on logistic or cleanup operations.
• Weather forecasting	• Much less reliable than other areas due to absence of reporting stations in polar region.
• Gas Hydrates	• Difficult to detect in sediments. • May cause gas-out of the mud during drilling or may over-pressure the well if the well is closed.

II. CURRENT TECHNOLOGY OF OIL/GAS EXPLORATION IN THE BEAUFORT SEA

During the last five years, the Canadian offshore industry has gained considerable Arctic experience through exploratory operations conducted in the Mackenzie River Delta and Arctic Islands in the Beaufort Sea. They have used engineering concepts closely adapted to local environmental conditions. The Canadian experience can be applied to Alaskan offshore exploration if proper attention is given to environmental differences which may exist between the Canadian and Alaskan Beaufort Seas, particularly, the fact that ice deformation north of the Mackenzie Delta is appreciably less than at sites of the Alaskan Beaufort Sea (Weeks, private communication). In addition, some near-shore exploration experience, gained over the past few years within the barrier islands at Prudhoe Bay, has allowed further identification of problems and applicable solutions.

Emphasis in this section has been placed on the exploratory drilling concepts (artificial sand/gravel platforms and grounded-ice platforms) that are limited to these shallow waters (20m (66 ft). In water depths greater than approximately 15m (50 ft), the formidable problem of moving and grinding ice ridges would have to be faced by any structure placed in such areas. Direct experience in this area, other than with drillships, has not been attained; therefore, concepts for deeper waters are not discussed in this section.

Table 2-1 presents a summary of development approaches which have already been demonstrated or are in planning stages by either Canadian or U.S. operators.

Most of the existing experience in Arctic exploratory drilling has been accumulated by Imperial Oil Ltd., recently renamed: Esso Resources Canada (ERC) Ltd.* (sand/gravel islands), Panarctic Oil Ltd. (floating ice islands), and by Dome Petroleum Ltd. (drillships). The discussion in this section concentrates on describing these concepts. Although drillships are mentioned only briefly, they were excluded from the scope of this review.

A. SAND/GRAVEL ISLANDS

1. Description

Sand and gravel islands are artificial structures composed of fill materials. In practice, temporary islands have been built from sand, gravel, and silt, or various combinations of these materials. Although only temporary islands (lasting one or two seasons) have been built to date, the technology apparently exists to construct permanent islands (lasting 20 to 30 years) which should be able to endure for the life of an oil/gas reservoir. The technology for permanent

* For simplicity the name Imperial Oil will be retained in the following parts of the report.

Table 2-1. Oil/Gas Industry Preferred Approach to Arctic Offshore Operation

Canadian Operators	Approach
Dome Petroleum	Drill Ships
Imperial Oil (ERC)	Sand/gravel islands, monocone
Panarctic Oil	Floating ice islands
Sun Oil	Sunken barges, sand/gravel islands

American Operators	Approach
Atlantic Richfield	Causeways
Exxon	Sand/gravel islands, ice islands (grounded), monocone/monopod
Gulf Oil	No independent research
Mobil Oil	No independent research
Shell Oil	Sand/gravel islands (?)
Sohio (BP)	Sand/gravel islands, causeways
Standard Oil (Chevron)	Sand/gravel islands, monocone
Union Oil	Ice Islands (grounded)

Supporting Industry	Approach
Global Marine	Surface effect vehicles
Reagan Company	Subsea completion
Sedco-Sealog	Ice cutter
Vetco Company	Subsea completion

islands is discussed in Section III of the report. Temporary islands constructed in the Mackenzie Delta since 1972 include 14 built by Imperial Oil Ltd. and two by Sun Oil Ltd. Three sand/gravel islands in the U.S. Beaufort Sea have been completed, one by Exxon in 4 feet of water west of Duck Island, and two by Sohio (BP) in 10 feet of water about 1.5 miles off the Sag River delta (Wilson, 1979) and in 3 feet of water.

Islands have been built within the fast-ice zone in water depths ranging from 1m (3 ft) to 14m (46 ft). An island in deeper water, 19m (63 ft) is now being built by Imperial Oil Ltd. Most of the islands constructed in water depths greater than 3m (10 ft) have been circular in shape while those in shallower depths have usually been rectangular. The rectangular shape is chosen where the wind is generally in one direction, and the smaller dimension can then be oriented to wave action and ice forces. The island surface area is usually about 2 to 2-1/2 acres, which is the minimum required to accommodate a drilling rig, supplies and personnel (Riley, 1976).

Islands have been built in both summer and winter. The choice of construction season and the method of construction depend on the availability of fill materials. In general, three methods of construction have been utilized.

a. Onshore Fill Material

In this method, onshore fill is transported over ice by truck and dumped at the island site. Such islands must be built in winter when the ice is strong enough to support heavy equipment. This method has proved to be economical and causes minimal environmental damage.

b. Offshore Fill Over 1 Mile of Site

This method utilizes dredged fill which is transported to the construction site by barge. The barges are then off-loaded at the island site by clamshell cranes. Such islands are built in summer months. Due to the high costs of fill transportation and handling, this method of construction is usually limited to shallower waters (see Table 2-5).

c. Offshore Fill Near Site

Two options are viable when nearby fill is available. In shallow water (<3m), clamshell cranes may be utilized to dredge fill material. If only silt is available, a sandbag berm may be used to retain the material at the site. However, silt islands can be used only after they are frozen since they have insufficient bearing strength when wet to support drilling equipment.

A second option, especially applicable to islands in deeper waters, is the use of a floating pipeline to transfer sand and gravel from the dredge to the construction site. This method of construction allows huge quantities of fill to be deposited in a short period of time. As much as 100,000 cubic yards per day, for example, can be dredged.

All of the methods cited above have been used by Canadian operators in the Mackenzie Delta. There is no apparent reason why similar techniques could not be employed in the Alaskan Beaufort.

2. Design Considerations for Sand/Gravel Islands

The design of an artificial island requires a consideration of ice forces, storm waves and tides, geotechnical and seismic properties of the seabed, and availability and engineering characteristics of the fill material. Additional constraints of timing and weather must be considered for islands which are constructed in spring or summer months.

a. Ice Forces

Ice forces acting on an island are caused by the movement of ice. Winter movement, when the landfast ice achieves a thickness above 1m (3 ft), may vary from a few meters (<15 ft) inside the barrier islands to hundreds of meters (<1000 ft) between the barrier islands and the shear zone. Spring and fall movements may be even much greater.

The force generated against an island is a function of the strength of the ice and its mode of failure. If an island is sloped and the surrounding ice is not solidly frozen (adfrozen) to the slope, ice movement usually results in bending of the ice and its consequent failure in flexure. Alternatively, if the ice is solidly frozen to the surface (adfreeze), a crushing or buckling failure may occur before the bond is broken. Static stresses produced by ice flexure on an island are considerably less than those produced by crushing or buckling. Dynamic ice forces acting on an island could induce some excess pore pressures where finer grain soils are utilized and this factor should not be overlooked.

If forces generated by ice motion are very large, an island may fail or be damaged. Figure 2-1 shows several possible failure modes resulting from ice forces (de Jong, 1975). The first (A) is an edge failure through the fill material; the second (B) is through the boundary between the frozen and non-frozen material; and the third (C) is along a plane through the sea bottom.

An edge failure (A), could affect operations but would not threaten the integrity of the island as a whole. Design criteria to prevent a failure of this type must consider a possible adfreeze condition. Sackinger (1977) performed tests to determine adfreeze shear strengths against steel cylinders. His results are plotted in Figure 2-2. He found that the non-saline adfreeze bond strength was about 1000 kPa (145 psi). The shear strength of ice around an island would tend to be lower since it is saline and because the adfreeze surface (sand or gravel) is irregular and presents a zone of weakness. Consequently, a reduced adfreeze shear strength of about 690 kPa (100 psi) is probably more realistic.

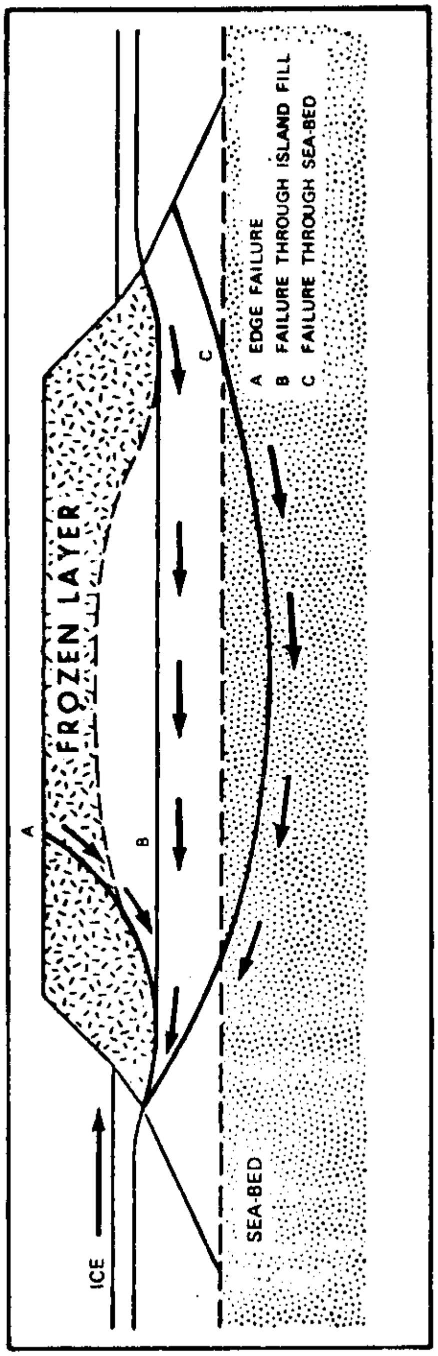


Figure 2-1. Possible Failure Planes of an Artificial Island (de Jong, 1975)

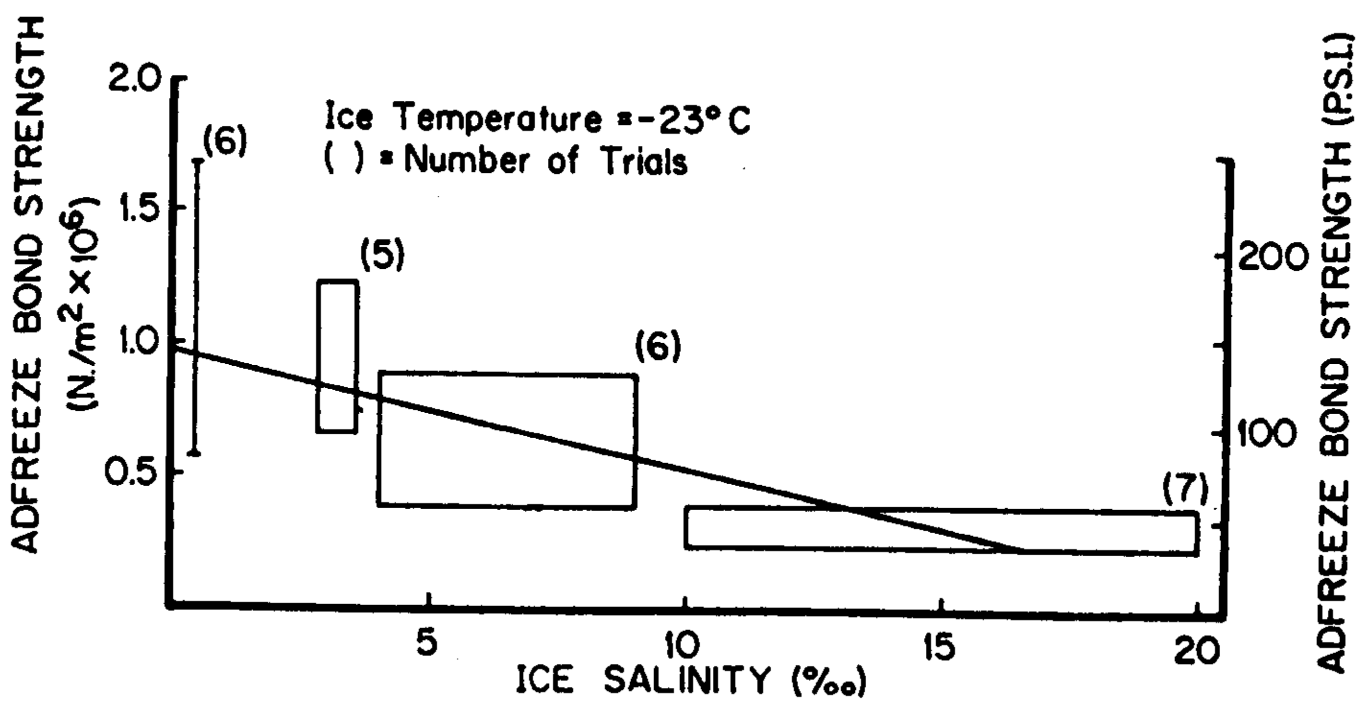


Figure 2-2. Adfreeze Bond of Saline Ice to Steel as a Function of Salinity (Sackinger, 1977)

The problem of ice override, which is another ice related hazard, was studied by Kovacs (1978), Weeks (1978), Hanson (1978), Shapiro (1977, 1978) and others. The ice override generally occurs when the ice sheet is not thick enough to be grounded in shallow waters. Hanson (1978) reported an advance of the ice of 35m (115 ft) in the Barrow Village and 140m (460 ft) on one of the small, low freeboard islands (Tapkatuk Island). Consequently, the artificial island design must take override into account by either breaking the advancing ice sheet or providing another form of protection. Once the ice is broken up and forms a rubble pile ahead of the island, it may become grounded and frozen solid, providing a barrier against ice forces and ice intrusion.

Shapiro (1977) has derived an equation for the force created by ice piling on a slope. The force per unit width of the slope if:

$$F = \rho_i \cdot g \cdot t \cdot L \, (\sin \beta + \mu \cdot \cos \beta)$$

where:

- ρ_i = the mass density of ice
- g = gravitational acceleration
- t = ice thickness
- L = length of ice sheet on shore
- μ = the coefficient of friction between ice and the slope
- β = the slope angle

Shapiro has estimated that the distributed ice-induced stresses are in the range 10 to 200 kPa (2 to 30 psi).

The second mode of failure (B) along an unfrozen boundary would be likely to occur when the upper frozen layer is shallow and the shear strength of the boundary layer which depends on overburden pressure, is low. Bafus (1975) has performed a thermal analysis of a saturated silt island built in 6.1m (20 ft) of water. The island was 7.6m (25 ft) high and the upper 1.2m (4 ft) contained saturated gravel. Figure 2-3 shows the freezing rate of the island using a winter temperature cycle similar to that of Barter Island in the eastern part of the Alaskan Beaufort. The graph illustrates that within six months, the island freezes to a depth of 3m (10 ft) but complete freezing to the sea bottom requires a period of five years or longer. This analysis indicates that the initial rapid freezing of the island would form a thick frozen layer with sufficient shear strengths to resist the ice forces. Also, utilization of induced freezeback techniques, such as heat pipes, would tend to enhance and accelerate soil freezing (Davison and Rooney, 1977).

The third type of failure (C), through the sea bottom, is a function of seabed shear strength which tends to increase with time as it becomes consolidated with the overburden pressure of island fill. Thus, an island becomes more resistant to failure as it ages. Riley (1976) measured initial shear strengths of the sea bottom in the Mackenzie Delta and found

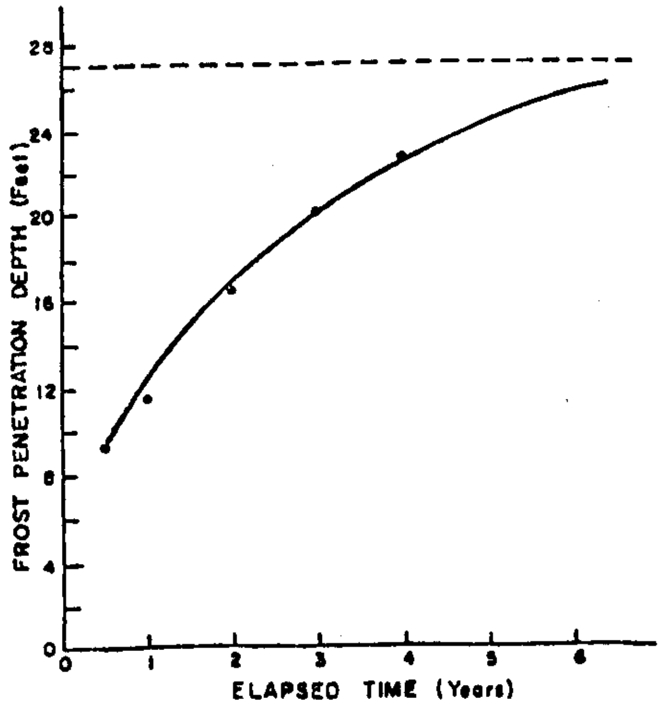


Figure 2-3. Simulated Elapsed Time to Reach an Equilibrium Freeze Front in a Saturated Gravel/Silt Soil Structure (Bafus, 1975)

them to be between 0.2 kg/cm^2 (3.1 psi) to 0.31 kg/cm^2 (4.5 psi). Considering the large base area of typical islands, these strengths should be sufficient to resist anticipated ice forces.

b. Waves and Tides

Waves and storm tides are critical parameters in determining the freeboard height of artificial fill islands. Insufficient height may result in inundation of the island by water or by water and floating ice. On the other hand, the economics of island construction dictate that excessive freeboard heights be avoided since costs increase in proportion to fill volume.

Standard design practice is to establish freeboard heights as a function of intended platform life coupled with the probability of encountering an extreme wave and storm tide height. This is best illustrated by way of example.

Assume a set of hypothetical conditions such as those shown in Tables 2-2 and 2-3. Some of the data were obtained from de Jong (1975). The tide values include 0.3m (1 ft) astronomical tide and 0.3m (1 ft) pressure effect.

It should be noted that both storm tide height and wave height vary with water depth. Storm tide height decreases with depth while wave height increases with depth. The return periods are reciprocates of the yearly probabilities of occurrence of the heights shown. A wave height with a 50-year

Table 2-2. Storm Tide Height, m(ft)

Water depth, m(ft)	3.0(9.5)	8.0(26.5)	12.6(41.5)	25.0(81.5)
10-yr return period	2.2(7.2)	2.0(6.5)	1.9(5.8)	1.5(4.9)
50-yr return period	2.6(8.5)	2.3(7.5)	2.0(6.5)	1.7(5.5)
100-yr return period	2.7(9.0)	2.4(8.0)	2.1(7.0)	1.8(6.0)

Table 2-3. Maximum Wave Height, m(ft)

Water depth, m(ft)	3.0(9.5)	8.0(26.5)	12.6(41.5)	25.0(81.5)
10-yr return period	1.6(5.2)	1.9(6.2)	2.9(9.4)	3.5(11.4)
50-yr return period	4.3(14.0)	6.1(19.8)	8.8(28.6)	9.1(29.9)
100-yr return period	4.6(15.0)	6.5(21.1)	9.1(29.6)	9.5(30.9)

return period, for example, could be expected to occur on an average of once every fifty years.

When a structure is designed, the selection of a return period depends on the proposed life of the structure. Exploratory drilling islands, for example, which are normally used for one year or less, can utilize a short return period. Return periods of ten years or less are standard practice. Thus, for example, Riley (1975) reports that exploratory islands built by Imperial Oil in water depths of 4.5m (15 ft) had a freeboard of 4.1m (13.5 ft). In deeper waters the freeboard was 4.5 to 7.5m (15 to 20 ft). On the other hand, a production island which may be used for 20 to 30 years must utilize a longer return period than that for exploratory drilling since it is vulnerable for a much greater period of time. A 100-year return period might be used.

Another problem which is posed by waves, and to a lesser extent by currents, is erosion. Even the normally low wave heights expected in the Arctic are capable of eroding an unprotected sand/gravel island rapidly. Short term protection against erosion depends greatly on water depth and island location. One of the strategies which has been used in Canadian island design, for example, has been to build rectangular islands in shallow waters close to shore where wave trains tend to come from a single general direction. Thus, by exposing the narrow edge of the rectangle to waves, erosion is reduced. Islands in deeper water, on the other hand, have been circular since waves may come from several directions.

Other measures have been developed to reduce wave erosion. Figure 2-4 shows a series of progressively more complex means of slope protection which are described briefly as follows:

(1) Completely unprotected slope suitable only for shallow water in protected locations;

(2) Filter cloth covered with wire netting - suitable for shallow locations;

(3) Small sandbags (2 ft^3, 280 lb) - applicable to water depths up to 2.4m (8 ft);

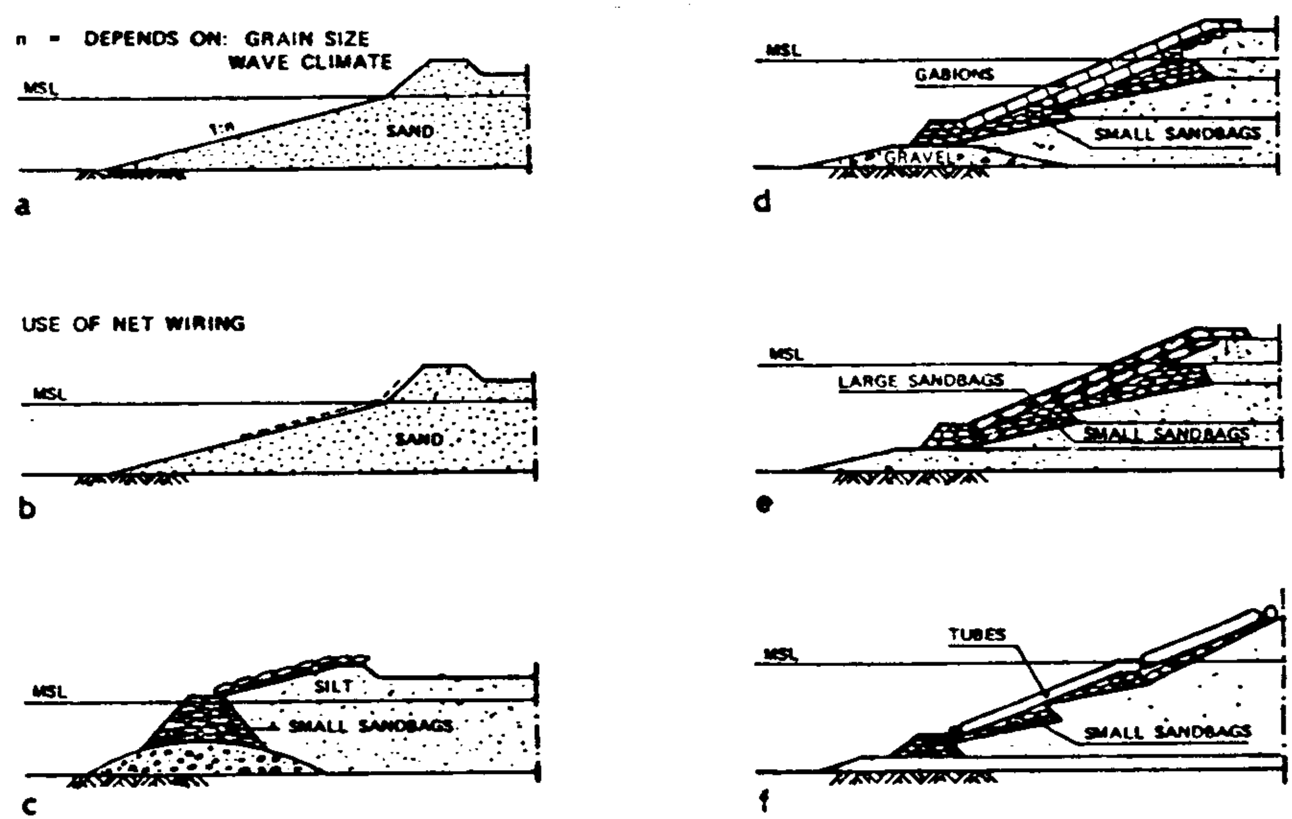


Figure 2-4. General Design of Shore Protection for Artificial Islands (de Jong, 1975)

(4) Combination of small sandbags overlain by 6-ton gabions (wire cages filled with rocks or sandbags). Construction proved difficult and was abandoned (de Jong, 1975);

(5) Combination of small sandbags and large sandbags (2 yd^3, 3 tons) - suitable for depths up to 14m (46 ft);

(6) Combination of small sandbags overlain by sand-tubes to reduce fill amount. Development was dropped because of difficulties in filling the tubes.

These measures apply primarily to shorter term situations and it is anticipated that more extensive design solutions would be attained for long term production facilities (see Section III).

c. Geotechnics and Seismicity

A consideration of onsite geotechnical factors is necessary to determine the settlement and consolidation of the seabed as a result of construction loads and loads imposed by drilling equipment and supplies. In addition, potential frost heave effects that may occur as a result of embankment or seabed freezing must also be assessed. The engineering properties of fill material must also be known to ensure that island slopes will not slide under their own weight or as a result of ice forces (Hydronamic, 1978). The settlement, consolidation, and freezing rate of the island itself are also determined by fill material characteristics. Other soil characteristics at the fill removal site are important operational considerations. The presence of cohesive soils or permafrost, for example, makes dredging more difficult. The thickness of overburden soils is also an important dredging factor.

Consequently, a great many types of data and information are required prior to island construction (Hydronamic, 1978).

Typical data needs include:

- Classification of the soil
- Geological profile
- Initial void ratio, permeability
- The compressibility index
- The coefficient of consolidation
- The permeability and specific weight
- Stress-strain diagrams
- Cohesion and angle of internal friction for various locaal conditions
- Freezing and thawing rates of soils
- Heave rates
- Permafrost
- Grain-size distribution
- Specific weight
- Frost susceptibility

In general, these data needs can be satisfied with boring samples and appropriate laboratory analysis. Sampling must be done at the construction site and fill source location some time before construction begins. Borings must also be taken on the island itself since many factors such as settlement and freezing rate must be monitored both during and after construction.

The availability of suitable fill materials especially sand and gravel, is critical for selecting island sites. In the Alaskan Beaufort area, there are a number of potential sources as summarized in Table 2-4. However, only two, subsea deposits and onshore pits located away from the immediate coast, appear to be viable in terms of quantity required and environmental impacts (Hopkins et al, 1978).

The seismicity of the Beaufort and Chukchi Basins presently does not appear to be a controlling parameter for offshore structural design in either area. This conclusion stems from a recently completed study done by Woodward-Clyde Consultants (1978) for the Alaska Subarctic Offshore Committee. Portions of this study are reproduced in Figures 2-5 through 2-9.

Figure 2-5 shows the study area. Figures 2-6 and 2-7 illustrate the expected return periods for maximum accelerations and velocities in the Beaufort and Hope Basins. It can be seen that the maximum lateral acceleration with a 100-year return period is 50 cm/sec (0.05 g) for the Beaufort Basin and less than 100 cm/sec^2 (0.1 g) for the Hope Basin.

Figures 2-8 and 2-9 show the normalized acceleration response spectra for the two Basins in comparison with suggested API spectra (API C and B) for alluvial soils. The accelerations predicted for both areas are below API limits.

Table 2-4. Sand and Gravel Availability

Mainland Beaches:	Small Amount Only
Offshore-Islands:	Substantial amount but irreversible environmental changes and damage will occur when dredging.
Offshore-Sea Bed:	Pleistocene gravel available in tens of meters thick formation under 3-10m overburden. Dredging environmental effects probably acceptable.
Onshore-River Beds:	Available in larger rivers but environmental effects may not be acceptable.
Onshore-Inland:	Available in borrow pits or large thaw lakes. Environmental effects acceptable if not close to shoreline.

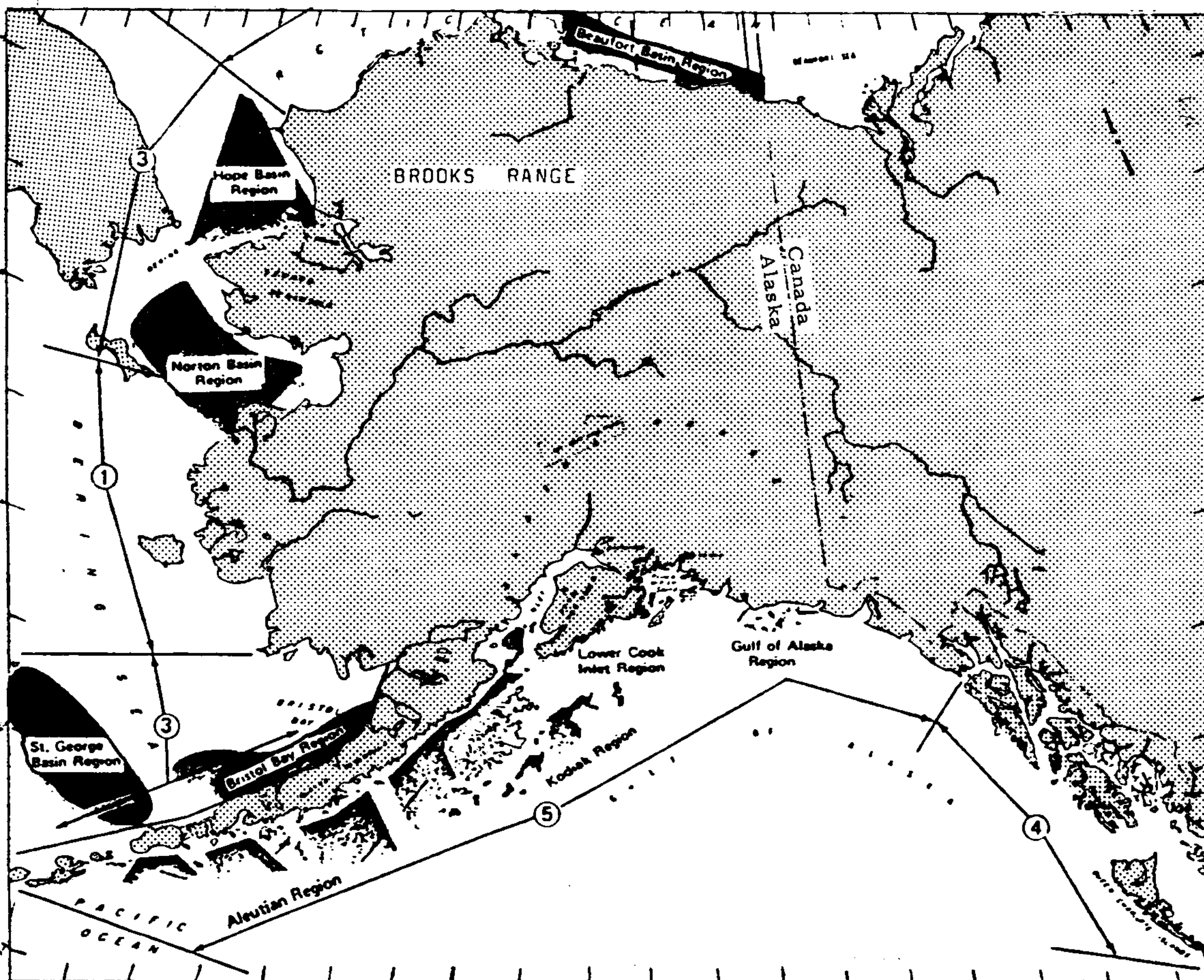
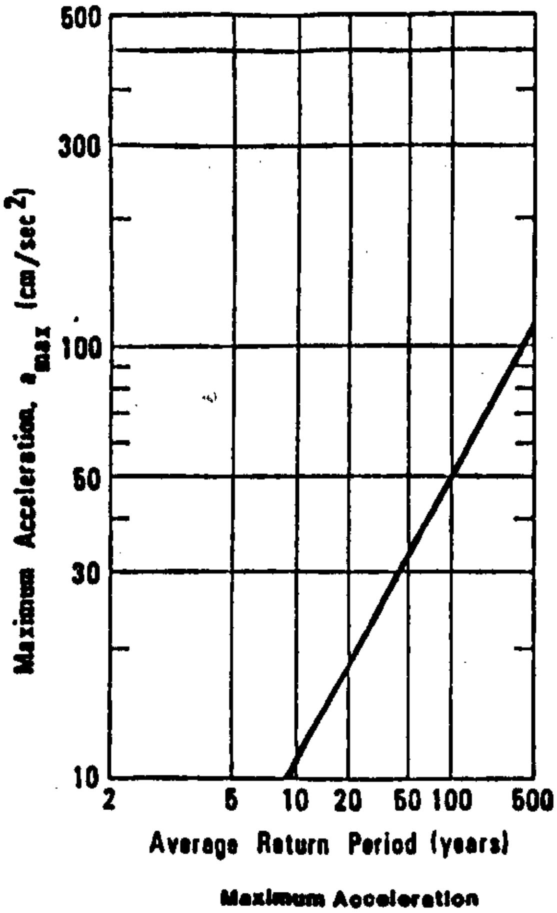
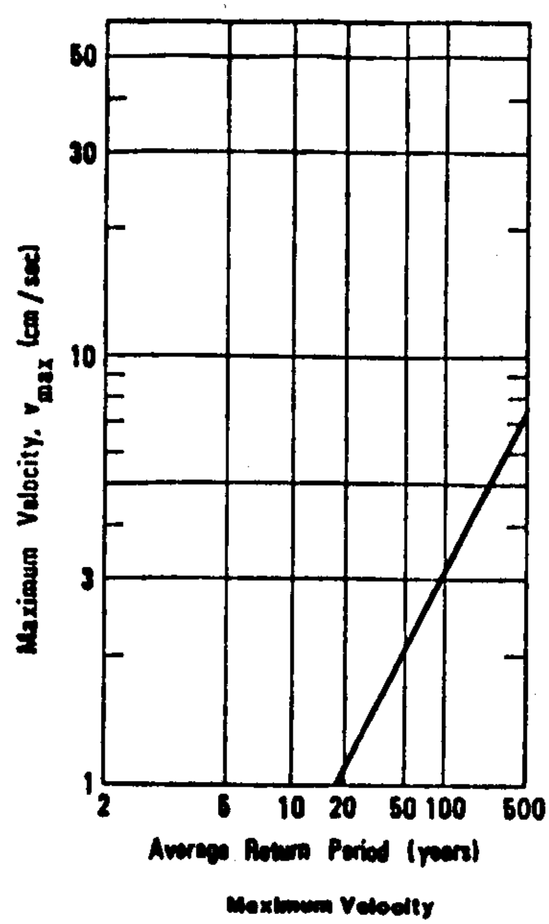


Figure 2-5. Location of Study Areas Relative to API Seismic Zones (Woodward & Clyde, 1978)





EXPLANATION

——— Values for this study

Figure 2-6. Return Periods for Seismic Velocity and Acceleration -- Beaufort Basin Region (Woodward & Clyde, 1978)

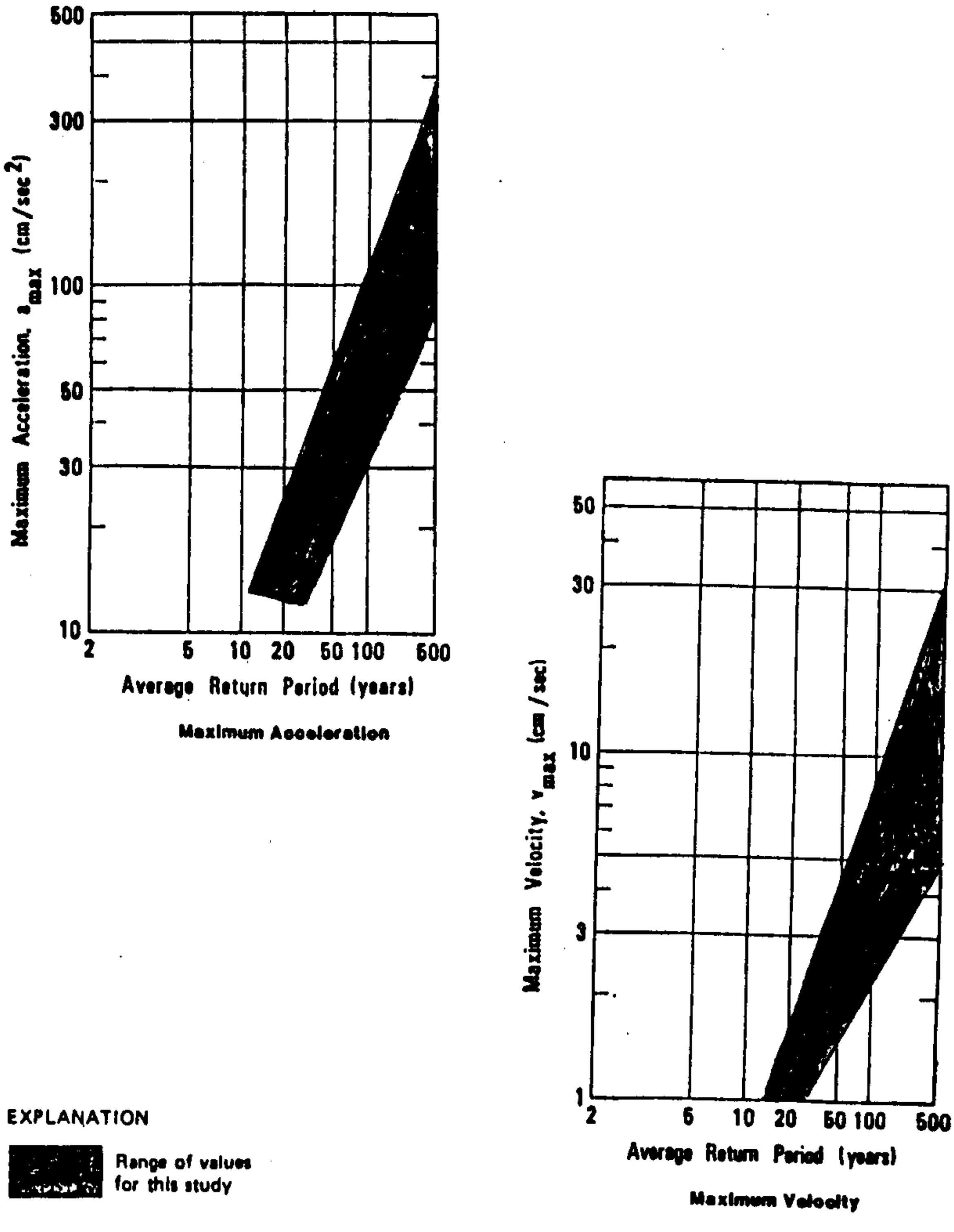


Figure 2-7. Return Periods for Seismic Velocity and Acceleration -- Hope Basin Region (Woodward & Clyde, 1978)

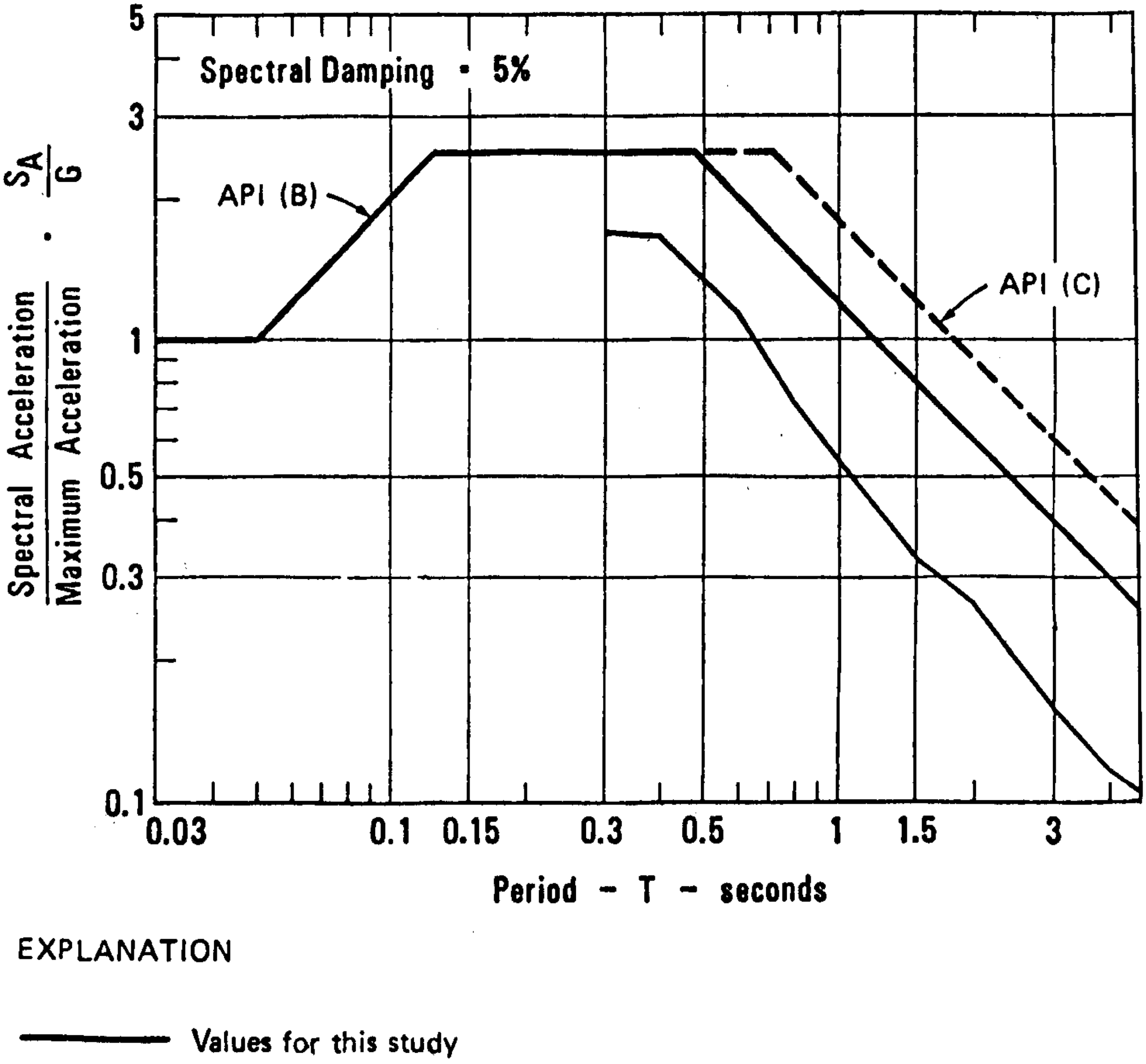


Figure 2-8. Normalized Acceleration Response Spectra -- Beaufort Basin Region (Woodward & Clyde, 1978)

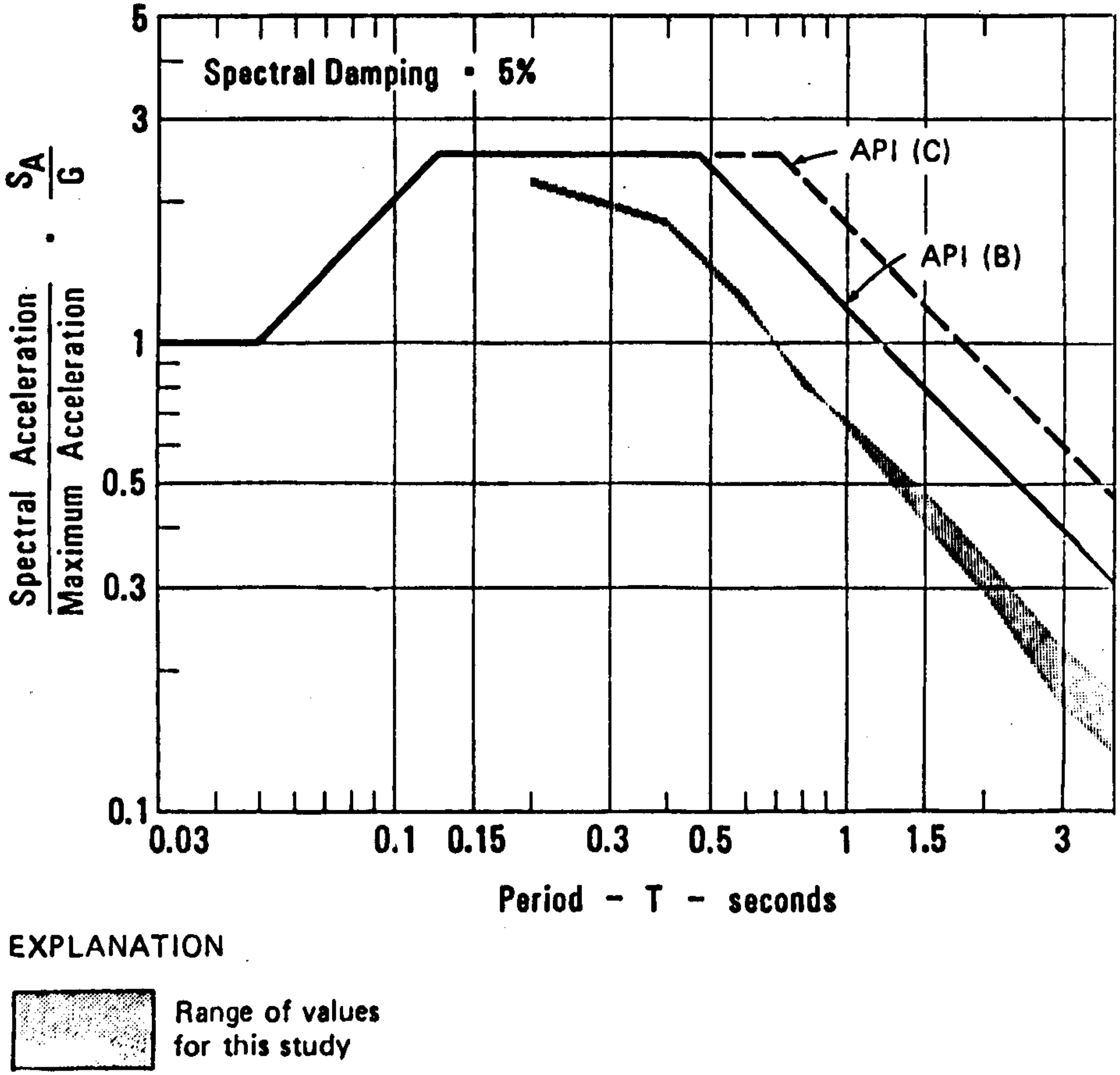


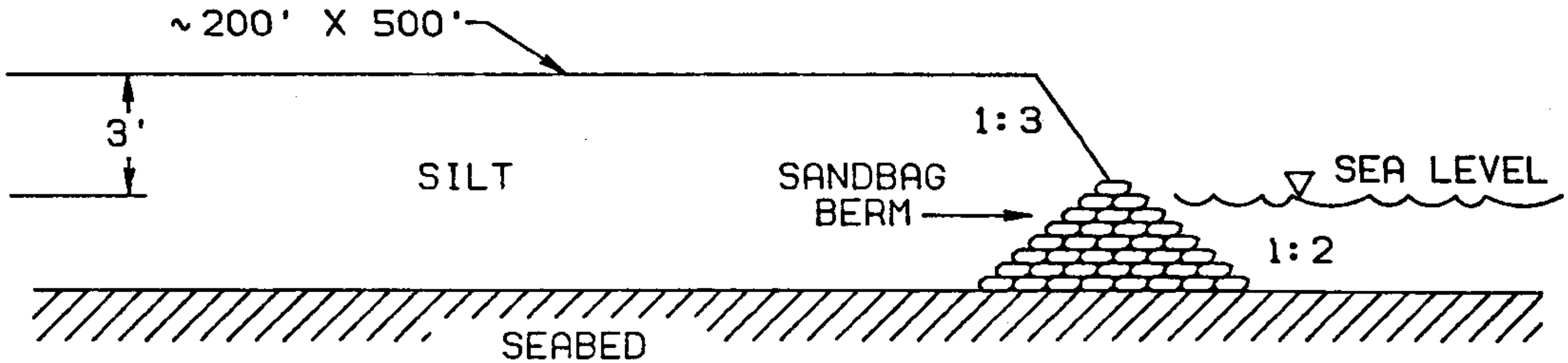
Figure 2-9. Normalized Acceleration Response Spectra -- Hope Basin Region (Woodward & Clyde, 1978)

3. Sand/Gravel Islands Built by Imperial Oil, Ltd (ERC, Ltd)

Imperial Oil has the most extensive experience in building artificial sand/gravel islands. They are presently building their 15th island in the Mackenzie Delta in a water depth of 19m (63 ft). Imperial has used construction methods and slope protection techniques described previously.

Figures 2-10 through 2-12 illustrate some of Imperial's island designs which varied as a function of water depth. For deeper waters, large sandbags (2 yd^3) were used to withstand the greater energy of storm waves (Cox, 1978). Figure 2-12 illustrates a somewhat different approach to the slope erosion problem. Rather than relying on elaborate methods of protection, this design incorporates a long gently sloping beach to protect the core of the island. Wave energy is thereby dissipated on the "sacrificial beach" which is also effective in grounding floating ice features, thus providing additional protection. The chief disadvantage to this design is that the beach fill may have to be replenished after storm activities if it is to remain effective. Such islands are most suitable where there is an abundant supply of fill material which is required for both initial construction and subsequent repair work.

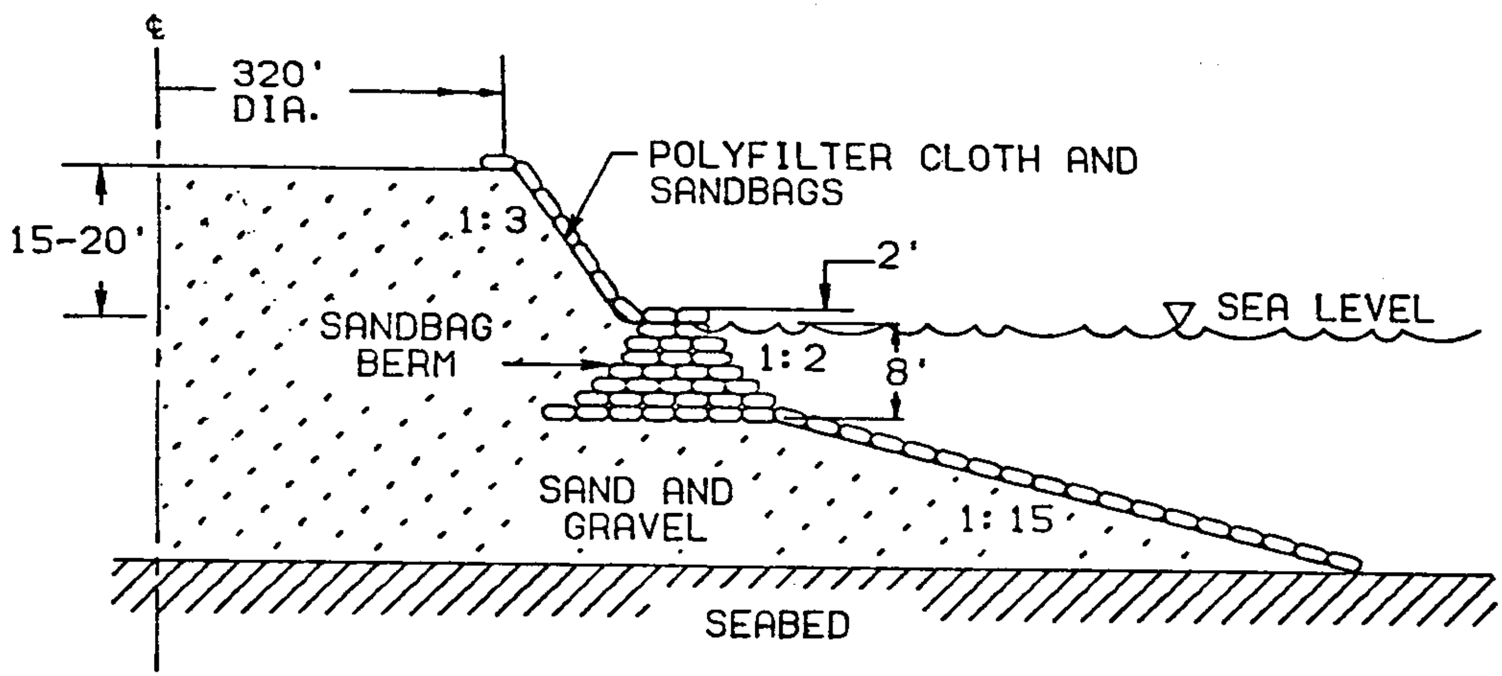
Table 2-5 gives a summary of Imperial Oil and Sun Oil designs. Figure 2-13 shows their locations in the Mackenzie Delta. All of the islands were built in either winter, spring,



CONSTRUCTION METHOD: CLAMSHELL

EXAMPLES:	WATER DEPTH
ADGO F-28	7'
ADGO P-25	5'
ADGO J-27	6'

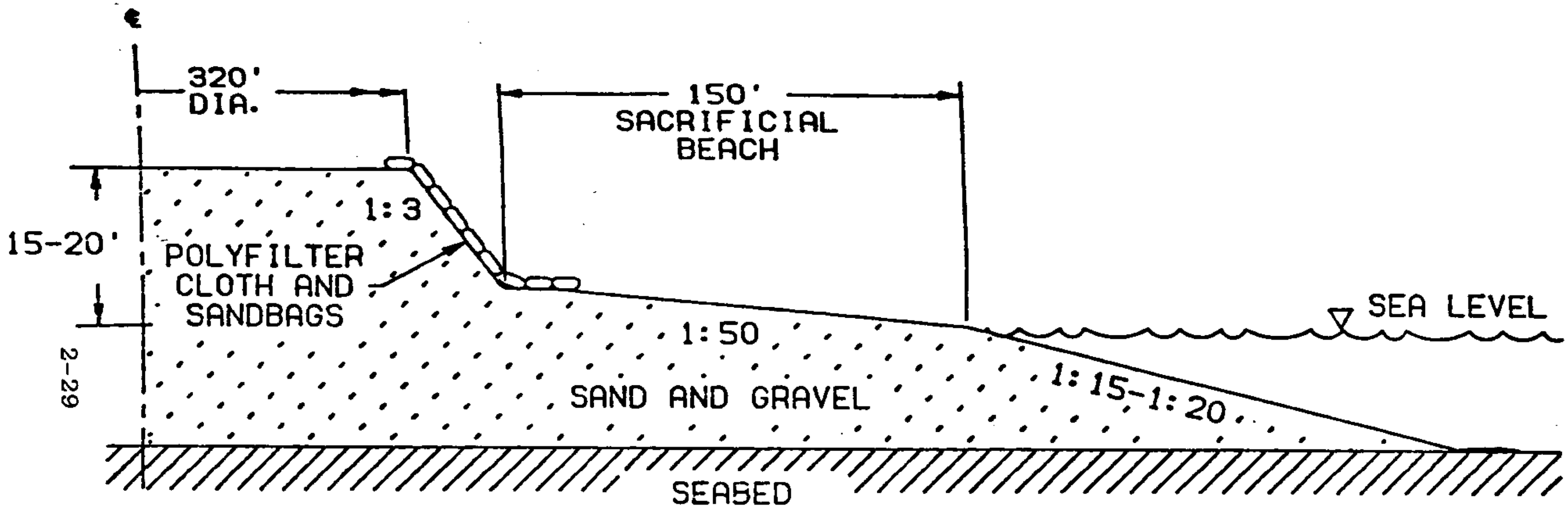
Figure 2-10. Typical Sandbag Retained Island <8 Foot Water Depth (Cox, 1978)



CONSTRUCTION METHOD: DUMP-BARGES AND CLAMSHELLS

EXAMPLES:	WATER DEPTH
NETSERK	15'
NETSERK NORTH	23'
KUGMALLIT	17'

Figure 2-11. Typical Sandbag Retained Island >8 Foot Water Depth (Cox, 1978)



CONSTRUCTION METHOD: DREDGE AND PIPELINE

EXAMPLES:	WATER DEPTH
ARNAK	28'
KANNERK	27'
ISSERK	43'

Figure 2-12. Typical Sacrificial Beach Island (Cox, 1978)

Table 2-5. Beaufort Sea Artificial Sand Islands (Cox, 1978)

Company	Name	Year	Water Depth	Type of Construction	Surface Size	Freeboard	Construction	Fill	Cost	Type
			FT.		FT.	FT.	DAYS	CU. YDS.	$MM	
Imperial	Immerk B-48	'73S	10	Dredge and Pipeline	300 dia	15	110	240m	5	Sac. Beach
Oil	Adgo F-28	'73S	7	Clamshells	150x600	3	30	48m	2.5	Sandbag Ret.
	Pullen E-17	'74Sp	5.5	Trucks Over Ice	225x375	10	40	84.5m	3	Sandbag Ret.
Sun Oil	Unark L-24	'74Sp	3.5	Trucks Over Ice	200x400	8	50	57m		Sandbag Ret.
	Pelly B-35	'74S	7.5	Barge Core and Clamshell	270x515	6	50	45m		
Imperial	Netserk B-44	'74S	15	Dump Barges and Clamshells	320 dia	15	80	400m	11	Sandbag Ret.
Oil	Adgo P-25	'74S	5	Clamshells	225x470	2	30	36m	2.5	
	Adgo C-15	'75W	5.5	Trucks Over Ice	165x515	10	42	92m	3	
	Netserk F-40	'75S	23	Dump Barges and Clamshells	320 dia	15	100	380m	15	Sandbag Ret.
	Sarpik B-35	'76Sp	13.5	Trucks Over Ice	320 dia	22	44	155m	5	
	Ikkatok J-47	'76S	5	Flat Barges and Clamshells	150x425	7	30	50m		
	Arnak L-30	'76S	28	Dredge and Pipeline	320 dia	17	35	1.5mm	5	Sac. Beach
	Kannerk G-42	'76S	28	Dredge and Pipeline	320 dia	17	30	1.5mm	3	Sac. Beach
	Kugmallit D-49	'76S	17	Dump Barges and Clamshells	320 dia	15	37	310m		Sandbag Ret.
	Adgo J-27	'76S	6	Clamshells	165x350	10	30	90m		
	Isserk	'77S	43	Dredge and Pipeline	320 dia	15	80	2.5mm		Sac. Beach
Sohio	Sag Delta	'77W	3	Trucks Over Ice	325x400	4	14	52m	1	

S-SUMMER W-WINTER Sp-SPRING m = thousands (10^3)
mm = millions (10^6)

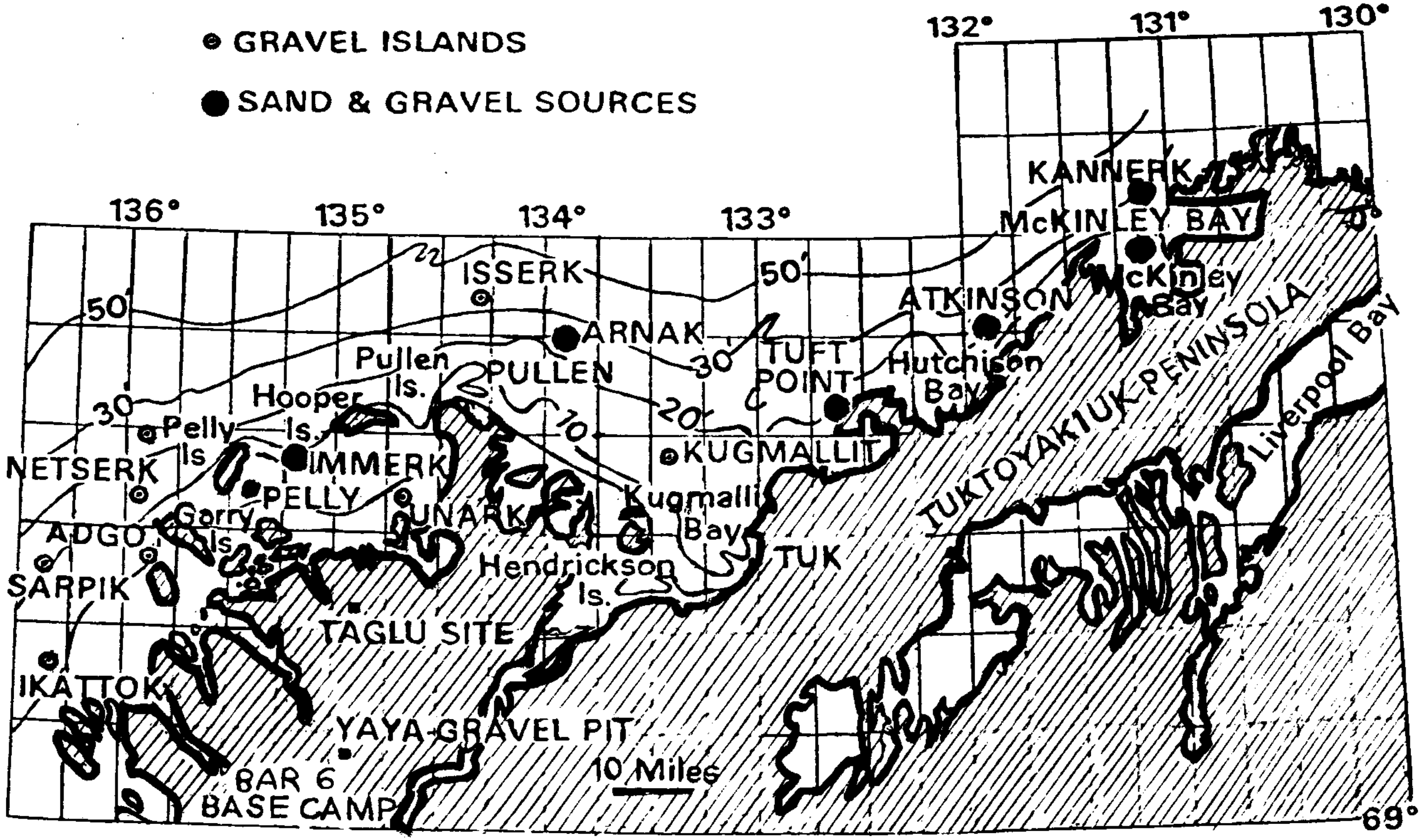


Figure 2-13. Mackenzie Bay Artificial Gravel Islands (Cox, 1978)

or summer, depending on water depth, availability of fill material, and construction method. Islands which were built in the spring and winter utilized trucks to transport the fill. Summer construction methods included clamshell dredges in shallow water and dredge and pipeline methods in deep water. The dredge and pipeline method is particularly effective for building islands rapidly. This is illustrated by the Arnak L-30 and Kannerk G-42 islands which required only 35 and 30 days of construction time, respectively. Both islands utilized a sacrificial beach design and consequently required relatively large volumes of fill.

The Adgo type of islands utilized onsite silt material excavated by means of a clamshell dredge. Drilling from these islands was possible only after they had frozen sufficiently to support drilling equipment weighing in excess of 50 tons (Riley, 1976).

4. Sun Oil Ltd. Sand/Gravel Islands

Sun Oil has built two islands, Unark and Pelly, whose location, design and construction data are shown in Figure 2-13 and Table 2-5, respectively.

While the main design criteria used for those islands was similar to those employed by Imperial Oil, they differ in design details.

The Unark location, built in the winter of 1974 for summer drilling in 1-1.2m of water (3.5 ft), was rectangular in shape with more elaborate slope protection than those described previously. The Unark Island sectional view is shown in Figure 2-14. The slope is protected by multi-layer filter cloth overlain with three layers of bags filled with sand containing 5 percent Portland cement (to bind the sand). On top of the sandbags, chain link fencing was placed, anchored at both the toe and top of the island and tied over with hogwire. Unark Island has survived several seasons as of this date.

The second island built by Sun Oil in the summer of 1974 was for winter drilling in a water depth of 2.4m (8.5 ft) whose location and design parameters are also given in Figure 2-13 and Table 2-5, respectively. Since transporting of gravel in the summer was difficult, it was decided to use the local seafloor silt as fill material. However, the silt could not support a drilling rig and, in order to save time, two railroad barges tied together with a superstructure were used. Figure 2-15 shows the cross section and plan section of the island. A berm was built to protect the barges against ice forces in the form of gabions (wire mesh cages filled with 2 yd^3 of sandbags). The space between the berm and the barges was filled with silt to a height of 0.3m (1 ft) above sea level.

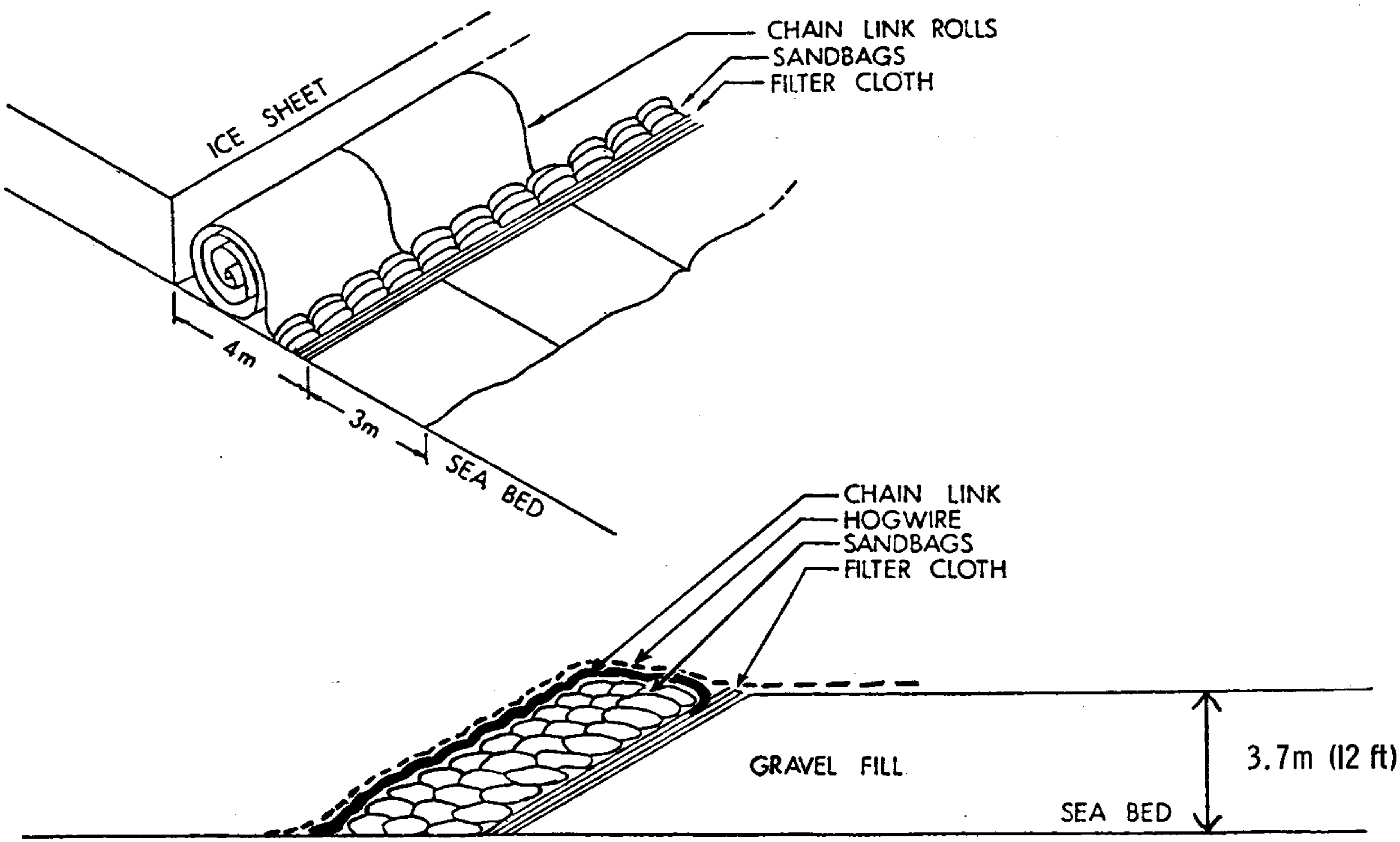


Figure 2-14. Unark Drilling Island -- Sectional View, Sun Oil, Winter 1974 (Brown & Barrie, 1975)

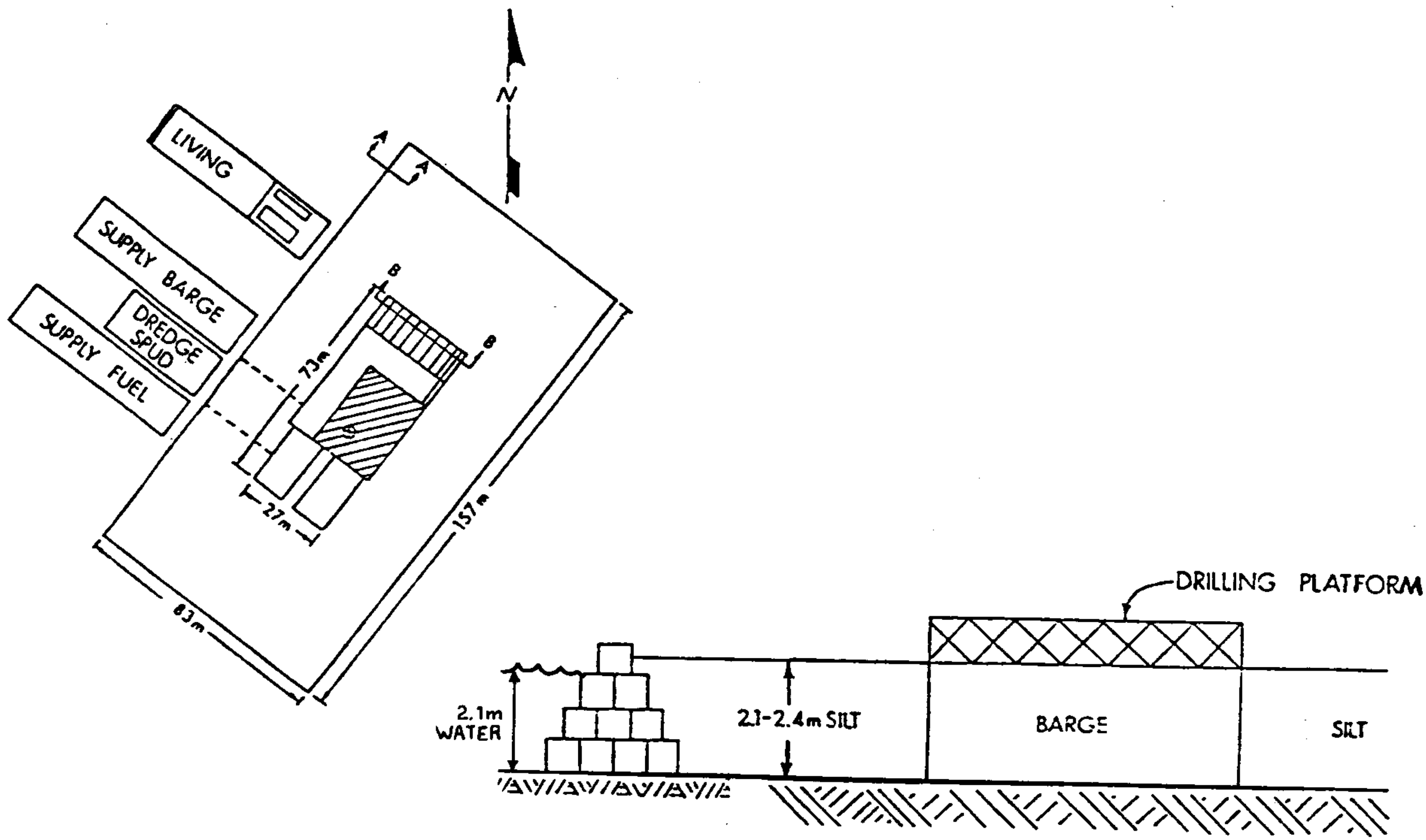


Figure 2-15. Pelly Drilling Island -- Sun Oil, Summer 1974 (Brown & Barrie, 1975)

5. U.S. Built Sand/Gravel Islands

Exxon built a gravel island in 1.2m (4 ft) of water near Duck Island in winter-spring 1978. The island has a gravel slope of 1:7 without any special means of slope protection. It is 122m (400 ft) in diameter and has a freeboard of 2m (6.5 ft). At the time of this report Exxon was conducting exploratory drilling from this island and completed the operation before June 1, 1979.

A sand/gravel island was built by Sohio (BP) in 3m (10 ft) of water about 1.5 miles off the Sag River Delta and at present exploratory wells are being drilled under state lease. The islands generally are similar to those built by Imperial but differ somewhat in design details.

Another Sohio Island in Sag River Delta (see Table 2-5) was built in 1977 and one well was drilled in the winter of 1977 and another in the winter of 1978.

6. Operational Experience and Economics of Sand/Gravel Islands

In general, the operational performance of sand/gravel islands completed to date has been good. No significant structural problems have been encountered during exploratory drilling. Most of the islands have been instrumented as a safety measure to detect the buildup of forces and to obtain engineer-data. The types of measurements included: permafrost monitoring with thermistors to determine the effect of fill overlying permafrost; consolidation monitoring using settlement sensors in the seabed; lateral displacement monitoring with inclinometers to detect movements due to ice forces.

No lateral movements due to ice forces were observed with the exception of silt-filled Adgo Island where a 2-inch lateral displacement was detected. Frost heave effects, if any, have not been identified.

Ice movement and ice stresses in the surrounding ice were also monitored using surveying equipment, bottom-anchored wire gauges, and ice-embedded strain gauges. Large ice motions were observed near some of the islands in deeper water. At Netserk F40 (in 7m of water), for example, over one mile of movement was noted during freeze-up in October 1975. This motion formed a grounded rubble pile 100m (330 ft) from the island (Cox, 1978). Sun Oil recorded ice stresses up to 1,000 kPa (150 psi) (Brown and Barrier, 1975).

The cost of construction of a sand/gravel island is very dependent upon fill availability. The cost of fill may vary from $2/cu yd. taken at the construction site, to $30 cu/yd when excavated at some distance from the site and transported by barge. This is reflected in the cost data shown in Table 2-5. As a rule, the highest costs per unit of fill are for the dump barge/clamshell construction method and the lowest are for the dredge/pipeline method.

Apart from the high cost of island construction, other factors, especially logistics, make Arctic operations among the most expensive type of offshore exploration. C. R. Hetherington (1976) of Panarctic Oil, Ltd. reports that drilling a 10,000-ft well from an ice platform in the Arctic Islands costs from $2.5 to $4 million and that Arctic offshore exploration costs will be ten times that of other parts of North America. Exxon estimated the cost of an exploratory well in the Beaufort offshore at $18 million (Wilson, 1979).

B. ARTIFICIAL ICE PLATFORMS

The use of artificially strengthened ice for structures is not new technology, and was initiated by the U.S. Navy in the 1950's (Masterson, 1978). Such structures have received considerable attention recently when their potential as offshore drilling platforms was recognized. Sixteen ice platforms have been built in recent years for this purpose. Two basic types of platforms have been developed: in deep, well protected water situations, floating platforms are used; in water depths less than 3m (10 ft), the ice platforms can be grounded. Both types are sensitive to ice motion. Lateral movements greater than 5 percent of the water depth may affect the structural integrity of the marine riser for the floating ice platforms, and of the subsea connector for the grounded ones.

1. Floating Ice Platforms

a. Description

Panarctic Oil, Ltd. undertook the exploration of a gas field in the Sverdrup Basin of the Canadian Arctic Islands. The Arctic Ocean, in this region, has water depths ranging from 60 to 400m (200 to 1,300 ft). It is covered with ice 10 to 11 months of the year and has limited open water areas appearing in August-September (Baudais, 1976). Because drill-ship operations are difficult at best in this environment, Panarctic started research in 1971 on the feasibility of using floating ice platforms. Ice movement, which was of primary concern during the drilling period was constrained by the nearby barrier islands. Measurements made over a number of years with theodolites, and later with tellurometers, have shown movement less than 3m (10 ft) over the projected drilling period. This extent of motion was found to be compatible with drilling operations. It is therefore a special situation which does not exist in the Alaskan Beaufort Sea. It enabled Panarctic to use the floating ice platform concept.

Flooding of the ice was begun in late November when the natural ice was about 0.6m (2 ft) thick, and continued to the end of January when the natural ice thickness was 1.5m (5 ft). After the moonpool opening was made, the flooding commenced with electric submersible pumps at a rate of 6.5 to 9 cm/day (2.5 to 3 in/day) covering a circular area of approximately

100m (330 ft) radius. It was important to maintain the low temperature of the ice during flooding (less than -5°C) (23°F) to prevent formation of brine pockets in the ice which would reduce its structural strength (Hood, 1976).

Total ice thickness after flooding varied from 3.7 to 5.3m (12 to 17 ft) depending on the weight of the drilling equipment which varied from 500 tons, for a 1,800m (6,000 ft) well, to 1,500 tons for deeper wells (Masterson and Kivisild, 1978). The natural ice deflected under the weight of the added ice, as shown in Figure 2-16, and a freeboard of approximately 0.6m (2 ft) was necessary to allow for an additional creep deflection of the ice during the drilling operation. The creep could amount to 10 percent of the total ice thickness (Masterson and Kivisild, 1978).

Special subsea blowout preventers were used to provide maximum protection against the loss of well control in the event of large unexpected ice movements. To satisfy a number of special requirements the entire drilling system had to: allow for limited horizontal movement and for vertical motion (1 to 2 ft) due to tides; provide for mudline suspension of all casing strings to minimize ice loading; provide for either manual or automatic closure of subsea blowout preventers in the event of emergencies; and operate without diver assistance.

Insulation was provided which consisted of 4-inch thick wooden rig matting and two 2-inch layers of urethane insulation (Baudais et al, 1976) to prevent the ice from melting under

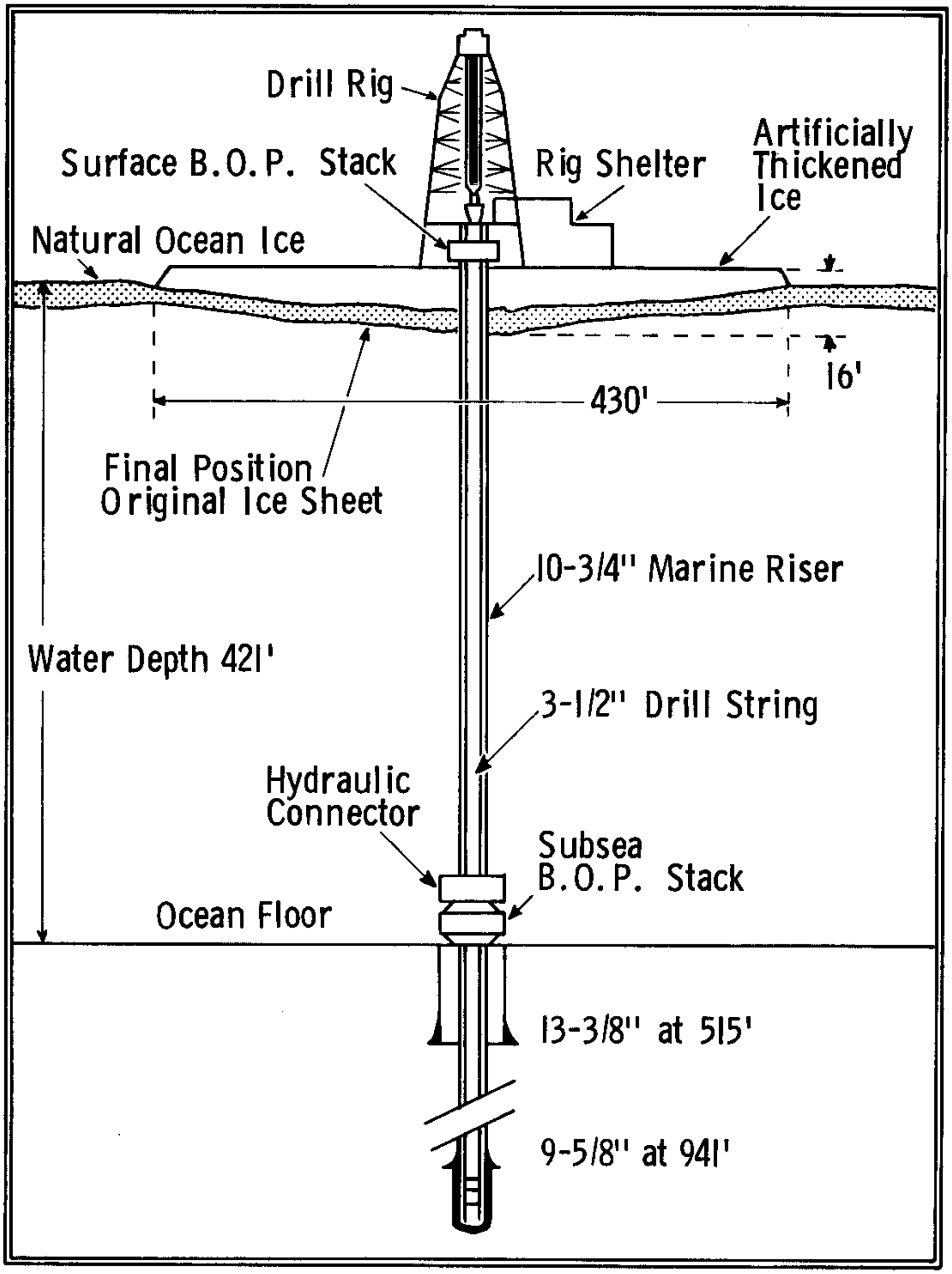


Figure 2-16. Schematic Diagram of Ice Platform Offshore Drilling System, Panarctic Oils Ltd. (Strain, 1975)

the drill rig and other equipment. The ice temperatures under the rig were monitored during the whole operation.

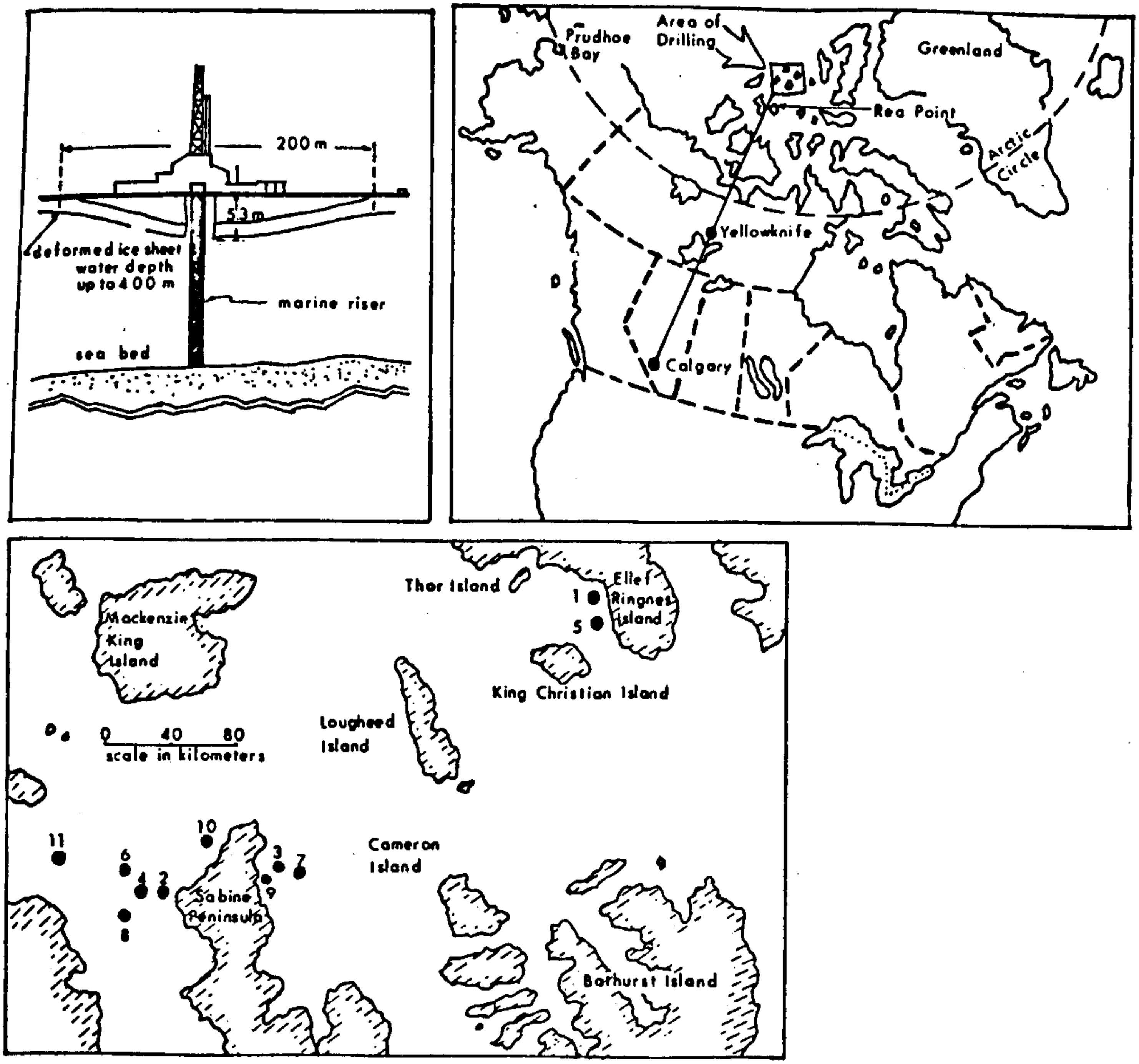
Time was a critical factor in the ice platform construction and drilling operation. The flooding could not start until the natural ice was thick enough to permit the passage of light, tracked vehicles and had to be completed by the end of January, leaving the February to April period for the drilling operation. In early May, the drilling equipment had to be removed from the platform because of gradual degradation in ice strength.

As of this date, Panarctic Oil had built 16 floating ice platforms. The majority were used for exploratory drilling with some reserved as relief well platforms. Eleven wells have been drilled successfully from these platforms. Figure 2-17 shows the location of 11 of these and the dates of drilling.

b. Design Considerations for Floating Ice Platforms

In the design of a floating ice platform, two parameters are considered: the bending stresses in the ice and the vertical deflections under load.

Stress analysis is performed assuming the platform to be an elastic, homogenous and isotropic plate supported on an elastic foundation. The maximum stress under concentrated load is:



Well Name	Date Drilled	Well Name	Date Drilled
1. Panarctic Jackson Bay B-16	May 1973	7. Panarctic N.E. Drake P-40	Feb 1977
2. Panarctic W. Hecla N-52	Apr 1974	8. Panarctic S.W. Hecla C-58	Apr 1977
3. Panarctic E. Drake I-55	Apr 1975	9. Panarctic Drake F-76	Feb 1978
4. Panarctic W. Hecla P-62	Feb 1976	10. Panarctic Roche Pt. O-43	Jan 1978
5. Panarctic Jackson Bay G-16	Mar 1976	11. Panarctic Cape Grassy G-20	Mar 1978
6. Panarctic N.W. Hecla M-25	Apr 1976		

Figure 2-17. Ice Platforms for Offshore Drilling (Masterson & Kivisild, 1978)

$$\sigma = 0.275\ (1 + \mu) \cdot \frac{P}{h^2} \cdot \log \frac{E \cdot h^3}{\rho_w \cdot a^4}$$

where:

μ = Poisson ratio

P = load, lb

h = ice thickness, in

E = ice elastic modulus, lb/in^2

ρ_w = specific weight of water, lb/in^3

a = radius of loaded area, in.

The rig weight was usually broken down in a number of circular loads and the stress beneath the largest load, i.e., the drilling rig at the moonpool, was calculated by superposition (Masterson and Kivisild, 1978). To maintain low deflections, the maximum ice stress was limited to 345 kPa (50 psi) although in some islands built earlier the stresses were only 170 to 210 kPa (25 to 30 psi (Hood et al, 1976). The presence of the moonpool in the center caused an increase in localized stresses by 40 percent or less and had no overall effect on deflection.

Vertical ice deflections are the most critical parameters in floating platform design. The instantaneous deflections under the weight of the drill rig are small at the stress levels mentioned above, but the creep deflections which are cumulative with time, could be large and may cause a loss of freeboard with subsequent flooding of the working area.

Figure 2-18 (top equation) gives the values of instantaneous deflection.

The creep deflection is a function of time as can be calculated from the lower equation in Figure 2-18. To eliminate the parameter K, which is highly variable with temperature, it is necessary to measure the creep deflection y_o for load P_o and ice thickness h_o, and then to take the ratio of y/y_o. The creep deflections can also be calculated assuming a lower ice modulus of 25,000 psi (Hood et al, 1976) as shown in Figure 2-18.

During the drilling operation ice platform deflections were closely monitored (as discussed below). Figure 2-19 (top right) shows that for Jackson Bay-G-16 platform, the creep deflection reached 0.3m (1 ft) in approximately 60 days.

Lateral ice movement was monitored and was not allowed to exceed 5 percent of water depth to maintain the structural integrity of the riser. In water depths of 305m (1,000 ft) or more, the allowable ice movement was limited by Panarctic Oil to 2 percent of water depth (Baudais, 1976) because at that time, the high pressure ball joint for the riser at the subsea BOP was not yet fully developed and the riser was rigidly attached to the BOP. When the ice movement reached 3 percent of the water depth, a disconnecting procedure was initiated.

Figure 2-18. Floating Ice Island Design

- ICE DEFLECTION CRITICAL

$$y_{max} = \frac{P}{8 \cdot \rho_W} \cdot \left[\frac{1}{\frac{E h^3}{12(1-\mu^2) \cdot \rho_W}}\right]^{1/2}$$ (TIMOSHENKO)

P - LOAD

ρ_W UNIT HEIGHT OF WATER

h - ICE THICKNESS

μ - POISSON RATIO

E - ICE ELASTIC MODULUS

- CREEP DEFLECTION

$$y = K \cdot \left(\frac{P}{h^2}\right)^n \cdot t$$ (MASTERSON)

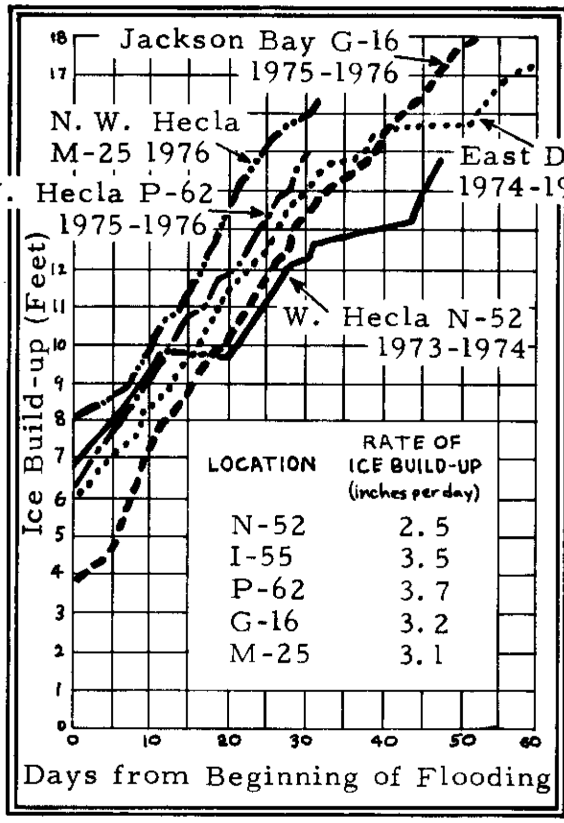
K - VARIABLE WITH TEMPERATURE

n - 2.2

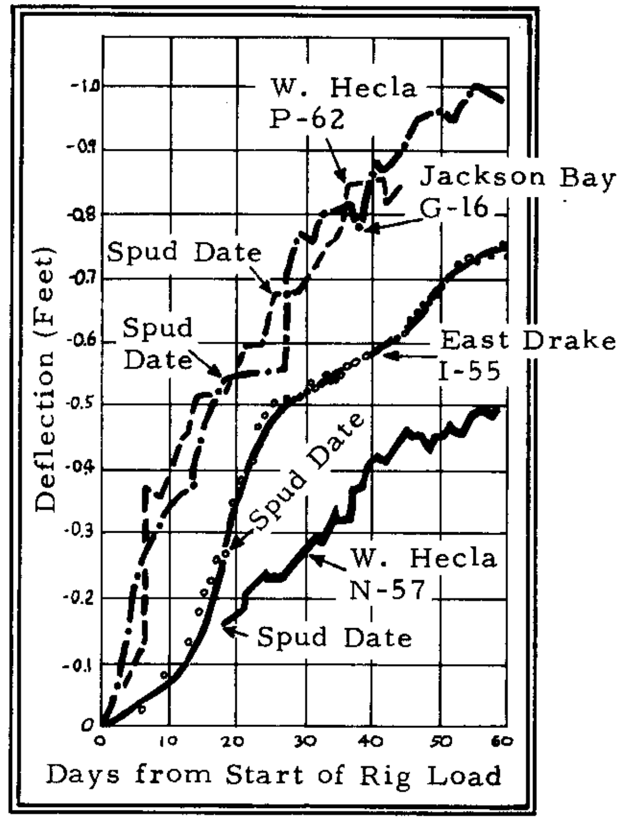
t - TIME

- TYPICAL VALUES

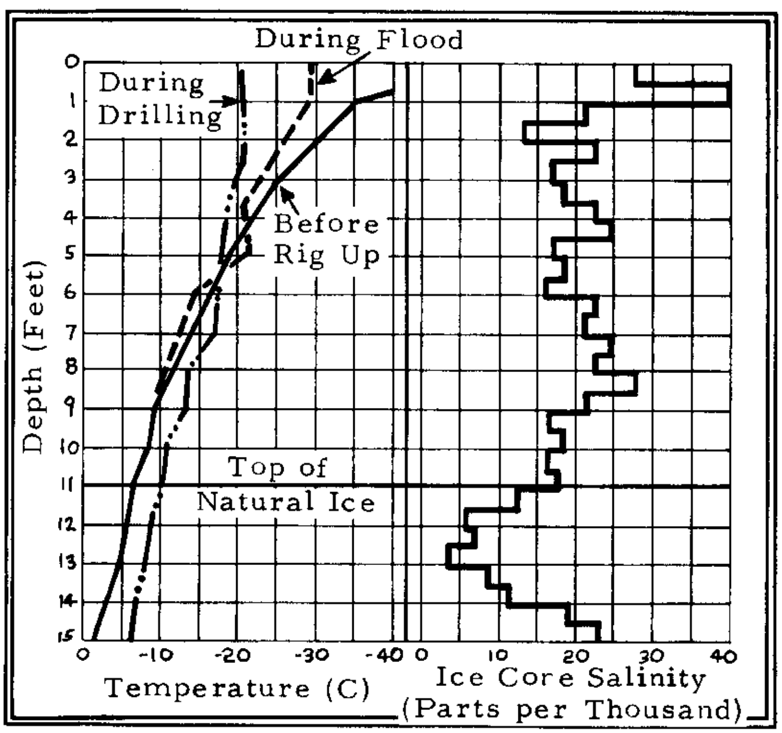
Max. FLEXURAL STRESS	$\lessapprox$ 50 psi
Max. DEFLECTION	$\lessapprox$ 10% ICE THICKNESS
ICE MODULUS (INSTANT)	$\sim$ 600,000 psi
ICE MODULUS (CREEP)	$\sim$ 25,000 psi
THICKENED ICE RADIUS	$\sim$ 300 ft.
ADDED ICE THICKNESS	$\sim$ 6 to 10 ft.



RATE OF ICE BUILD-UP



ICE PLATFORM DEFLECTION UNDER RIG LOAD



TYPICAL TEMPERATURE AND SALINITY PROFILE AT EAST DRAKE I-55

Figure 2-19. (Baudais, 1976)

c. Operational Experience and Economics of Floating Ice Platforms

Monitoring the performance of a floating ice platform during its construction and drilling periods is a prerequisite to a successful operation. During construction at East Drake I-55, the rate of ice buildup and ice temperatures were measured and some of the results are shown in Figure 2-19. As mentioned previously, the ice surface temperature during flooding was kept below -5°C (23°F) and the rate of ice growth was between 2.5 and 3.5 in/day. During the drilling operation, vertical deflections, ice temperatures and ice strength were monitored. The deflections were measured with standard surveying techniques, with float gauges floating in diesel oil-filled pipes, or more recently, with laser leveling devices. The creep rate shown in Figure 2-19 was observed closely since an increase in creep rate with time would indicate the beginning of a tertiary creep and imminent failure of the platform. None of the platforms built suffered such a failure (Masterson and Kivisild, 1978).

Ice temperatures were monitored at several locations using strings of pre-wired thermistors embedded in the ice at various heights. These measurements are plotted in Figure 2-19. Also shown is the ice salinity from borehole samples as a function of depth. Ice strengths were obtained throughout the ice depth by borehole hydraulic jack instruments developed specially by Fenco Consultants. Strains in the ice were measured using 3m (10 ft) long wires embedded in the built-up ice. Three gauges were placed in a rosette fashion at various vertical heights within the ice. In addition, close monitoring of ice movement was conducted using instrumentation discussed previously.

As mentioned before, time was a very important element in the construction and operation of an ice platform. In the period of December through April (5 months), an island had to be constructed, drilling equipment installed and drilling operations completed. For this reason, the maximum depth of a well which could be drilled was less than 10,000 ft (Strain, 1975).

The average cost of a 1,525m (5,000 ft) well drilled from an ice platform was $2.5 million as reported by Baudais (1976) and the construction cost of an ice platform was $0.5 million, leaving $2 million for rig costs, drilling operation, transportation, etc. (see also p. 2-38). Of course, the cost would be higher by 30 percent or more in 1979 dollars.

2. Grounded Ice Platforms

a. Description

A grounded ice platform was built in the winter of 1976-77 by the Union Oil Company in 3m (10 ft) of water in the East Harrison Bay (Brinker, 1978). The island consisted of a grounded rectangular drill pad enclosed by a grounded ice ring with an ice-free moat outside, as shown in Figure 2-20. The natural ice thickness at the beginning of flooding was approximately 0.5m (1.5 ft) and at the end it increased to 2m (6.5 ft). It was further thickened by flooding to 3.6m (12 ft) to ground it and to provide lateral resistance. The 0.6m (2 ft) freeboard was considered sufficient to allow for storm tides. The drill pad was 63m x 114m (206 ft x 375 ft).

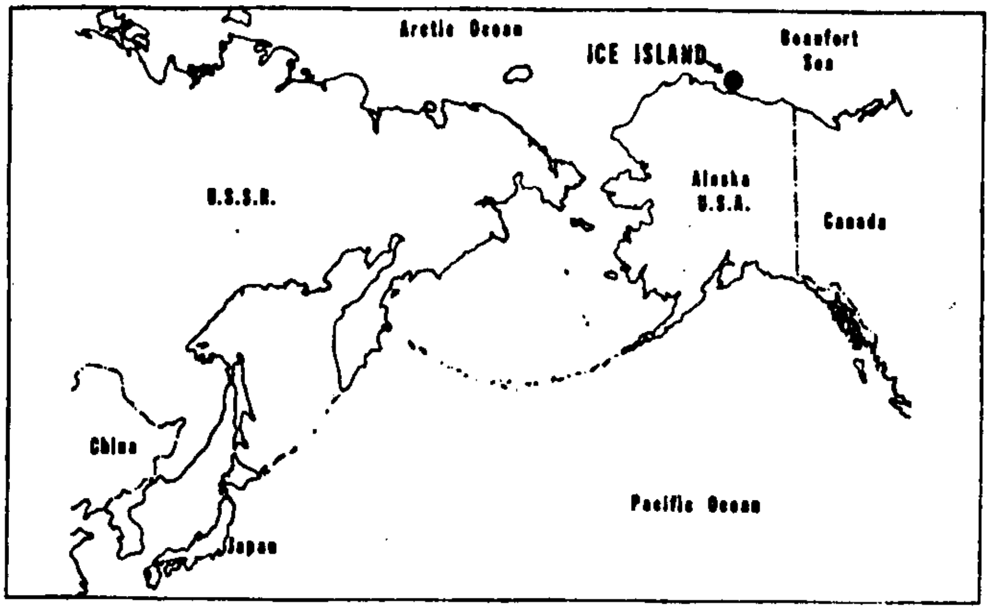
Simultaneously, a protective ice ring was built 4m (13 ft) thick, 21m (69 ft) wide and 300m (1,000 ft) in diameter. Its purpose was to protect the drilling pad from ice movement and to form a berm to contain oil in case of a spill. Adjoining the ring, an emergency relief pad was also built for drilling a relief well in case of a blowout (Figure 2-20).

Additional protection against ice movement was provided in the form of a 3.0m (10 ft) moat cut with the trenching machine. This was kept free of ice by using a crane with a clamshell bucket to break up and to remove newly formed ice. Approximately 7 to 15 cm (2.8 to 6 in) of new ice was formed every day (Brinker, 1978).

To prevent the ice from melting under the drill rig, wooden boards and insulation mats having a total thickness of 0.6m (2 ft) were placed between the ice surface and the rig.

b. Design Considerations

The design considerations for this type of structure were simplified since the open-water moat virtually isolates



LOCATION

SCHEMATIC

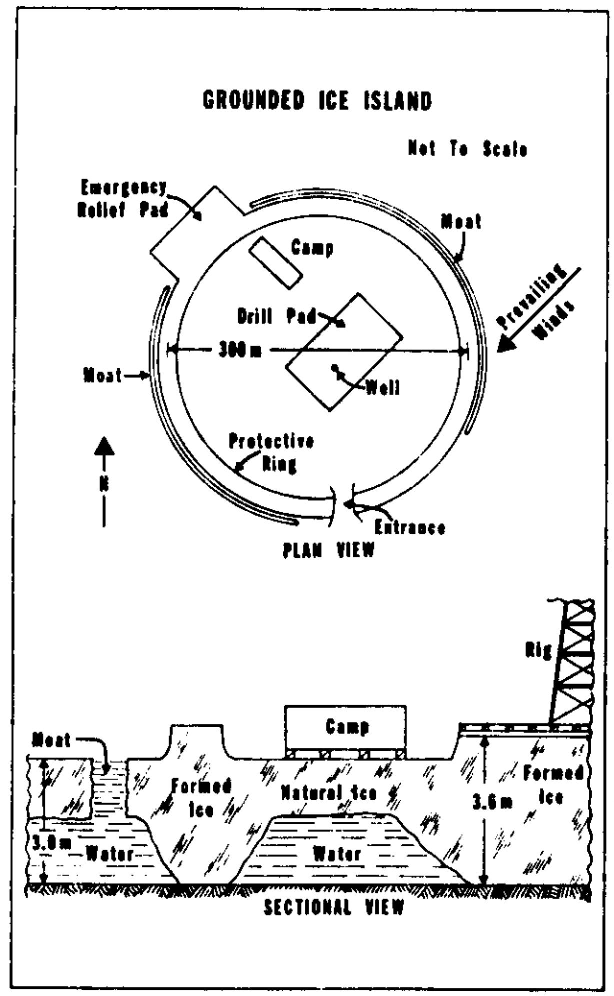


Figure 2-20. Grounded Ice Island, Union Oil, 1976-77 (Brinker, 1978).

the platform from ice movement and ice forces. Ice movement outside of the moat was closely monitored. Any invasion of the ice beyond the moat was considered an emergency requiring well shutdown and suspension of drilling operations.

The drill rig weight was distributed through the boards so that the compressive stresses in the ice were only 70 kPa (10 psi). The design was quite conservative in that the stresses were kept substantially below ice crushing pressure which was assumed to be at least 2070 kPa (300 psi). It was also considered important that the temperature of the ice below the pad be maintained below -5°C (23°F). The insulation provided for this purpose by Union Oil achieved that goal.

3. The Operational Experience and Economics of Grounded Ice Platforms

Figure 2-21 shows the Union Oil time schedule for the ice platform described above which shows timing was a critical factor in construction and operation of that structure. Within five months, the platform was built, and a 3,000m (10,000 ft) well was drilled. All equipment was removed from the platform by mid-April.

Ice movement was monitored outside of the moat through the period of February 25 to May 25, 1977. The movement was gradual and less than 1m (3 ft) in any direction (Brinker, 1978).

TIMETABLE: 1976-77 ICE ISLAND

ACTIVITY	START	FINISH	DURATION
FREEZE UP OF HARRISON BAY	EARLY OCTOBER		
SURVEY LOCATION	NOV. 2	NOV. 5	3 DAYS
CONSTRUCT ICE ISLAND	NOV. 5	JAN. 20	76 DAYS
SET UP DRILLING RIG	JAN. 20	FEB. 17	28 DAYS
DRILL WELL	FEB. 17	APRIL 6	48 DAYS
MOVE OFF ICE ISLAND	APRIL 6	APRIL 16	10 DAYS
COLVILLE RIVER FLOODED OVER ICE	JUNE 3	—	—
ICE ISLAND MELTED	JULY 14	—	—

Figure 2-21. Timetable, Union Oil (Brinker, 1978)

The total cost of the operation was $8 million of which 12 to 20 percent was for the cost of the ice platform construction. Utt (1978) estimated that the cost of a grounded ice platform would be one-quarter of a gravel island built at the same water depth.

C. ADDITIONAL EXPLORATORY DRILLING CONCEPTS

This offshore Arctic exploratory drilling experience report would not be complete without mentioning Dome Petroleum Ltd. drillship operations. Dome, through its subsidiary, Canadian Marine Drilling Company, is exploring for oil and gas reservoirs north of the Mackenzie Delta in water depths below 200 ft.

The Canadian fleet consists of three drillships with reinforced hulls for ice forces (Explorer I, II and III), seven Class II icebreaker supply boats, three barges, and one oceangoing bulk carrier.

To safeguard against ice movement, the drillship moorings had acoustic quick disconnects and the subsea BOP was mounted below the mudline. The BOP disconnect flange had to be 4m (13 ft) below the mudline in a caisson or in a "glory hole to avoid the danger of ice islands scouring the seabed (Todd, 1978).

Because of the short drilling season (about 45 days), and the need for standby relief equipment required by Canadian regulations, the cost per well was very high. Dome reported operation cost in 1975 in excess of $130 million and the cost per well in excess of $30 million. Also reported was an uncontrolled gas and water flow from the subsea wellhead caused by sudden ice intrusion which occurred in spite of all safeguard measures.

Drillships would probably not be used in the exploratory drilling in the first Beaufort Sea lease sale tracts because of the shallow water. The same probably applies to semi-submersibles. Jackups have not been used to date for offshore Arctic operations. They are being considered in industry studies. There are areas in the Alaskan Beaufort offshore such as locations between the mainland and the barrier islands where the ice movement in winter (January-May) is on the order of only a few feet. If the jackup legs are thermally protected against ice adfreeze and a small ice movement, and if some modifications are made to winterize them and to allow for towing over ice, winter operations in the Arctic offshore may be possible. Once available in the area, jackups could perhaps be used for summer drilling in protected areas as well.

Some of the mobile systems discussed further such as monopods or monocones, could also be used for exploratory drilling. Matters of safety, economics and local conditions determine the applicability of such systems for either field exploration, or development and production.

The short drilling season affects all the drilling concepts for offshore Beaufort Sea operations. To extend this drilling period, a modular platform design was proposed by Rothrock and Morgan (1972). Their platform consists of a number of watertight modules which could be floated to the required location and quickly assembled using a unique double-conical frustum connector and tension cables. The platform has an installed moonpool, and all drilling and support equipment can be placed over it. The platform will distribute the loads over a wide area, and in event of ice breakthrough, if not grounded, its buoyancy permits continued support of the installed equipment. The platform could be disassembled even if partially frozen in.

In closing the discussion of exploratory drilling, it must be realized that, at the present time, there are no published design rules or criteria for the concepts presented. Soon, definite requirements for establishing sand/gravel islands and ice platforms may be necessary. The facts presented here should provide some basis for compiling such regulations. Also, there are no completed verification procedures for either the acceptance of these structures or for the safety standard required. It would be useful if these be compiled before any major drilling activity is contemplated in the Beaufort or Chukchi Sea. Experience available from Canadian and Alaskan offshore drillings and from onshore Prudhoe Bay operations should be used in preparation of the above documents.

D. LOGISTICS SUPPORT OF ARCTIC OFFSHORE OIL/GAS OPERATIONS

The limited accessibility to the northern Alaska offshore, combined with a severe climate, requires careful planning for the transportation of heavy equipment, personnel, and for the supply of material in support of the oil/gas operation. Even then, unexpected changes in weather may upset the best plans, such as those experienced by Prudhoe Bay Sea Lift pipeline barges stranded offshore during summer months (August, September of 1975) as a result of heavy ice invasion along the Arctic coast. Consequently, logistics planning should always provide for an alternate contingency in case the main supply becomes inaccessible. The existence of the Alyeska highway from Fairbanks to Prudhoe Bay improves the logistic situation, but it is still necessary to transport the material from Prudhoe Bay, to bring in the heavy equipment by barges, and to shuttle the personnel.

The construction of the Alyeska pipeline and of Prudhoe Bay production facilities has provided valuable experience in Arctic logistics which was reviewed by Jahns (1978).

Marine transport by barges through the Beaufort Sea is economical but it relies on an ice-free water path in summer which in some years may not occur. For barge unloading, causeways may provide the safest and least environmentally damaging means of heavy load transfer to onshore sites.

Aircraft, both fixed wing (Hercules 130, Twin Otter) and helicopters (Bell 205) were frequently used for transport of loads up to 20 tons in the case of the Hercules. This is expensive, requires construction of landing strips or pads, and is sensitive to weather conditions.

Rolligons are the off-road vehicles most used on the North Slope. They can cross the tundra after it dries and can be used on relatively thin ice (2 ft) because of the low ground pressure they exert.

Air cushion vehicles (ACV's) have been of relatively little use in Alaskan oil/gas operations except for limited employment of Canadian Bell Voyager and air cushioned barges.

Existing transportation means are now adequate to support exploratory activities, but are not sufficient for year-round support of production operations in offshore oil/gas fields. For that purpose, construction of additional permanent roads, causeways, and perhaps a wider use of more reliable ACV's would be required.

Table 2-6 presents a listing of transportation means, concerns, and gaps still existing in technology and baseline data.

Summarizing the transportation problem, four modes of transport can be considered:

1. <u>Marine, By Ships, Barges and Tankers</u>

The constraint on this mode is the short season (approximately 60 days) and the shallowness of the water in the

Table 2-6. Logistics Support

TYPE	EXAMPLES	CONCERNS	TECHNOLOGY NEEDS	DATA NEEDS
MARINE	• SURVEY SHIPS • SUPPLY BARGES	• SUMMER ICE • OPER. COST • HAZARDS	—	• IMPROVED ICE FORECASTING
ICE SURFACE	• TRUCKS • SLEDS • ROLLIGON	• ICE THICKNESS • SNOW DRIFTING • ICE MOVEMENT RIDGING	• RIDGE-CROSSING TECHNIQUES	—
AIR	• FIXED-WING • HELICOPTER	• RUNWAY • WEATHER • DOWNTIME COST	—	—
AMPHIB-IOUS	• ACV	• RELIABILITY • ICE RIDGE CROSSING	• IMPROVED RELIABILITY • INCREASED GND. CLEARANCE	—
ALL-WEATHER YEAR-AROUND	• CAUSEWAYS	• ICE PRESSURE • ICE OVERRIDE • WAVE EROSION • GRAVEL AVAIL. • MARINE BIOTA	—	• ICE PRESSURE OVERRIDE • OCEANO-GRAPHIC • BENTHIC LIFE

gently sloping Beaufort Sea which puts a limitation on the draft of floating vessels.

2. Terrestrial-Overland

There are constraints on this mode of transportation. From late spring until the early fall (June to early October) travel across the tundra with heavy-wheeled and tracked vehicles is not permitted because of the fragility of the thawed active vegetation layer above the permafrost which would be affected by the passage of any high ground pressure wheels or tracks. Only air cushion vehicles and special low ground pressure rolligons could be considered.

3. Terrestrial Over Snow Or Ice

This mode of transportation is possible in winter when the sea ice is thick enough to support moving loads. Additional support may also be gained at some locations by constructing ice bridges or ice aggregate pads. When the ground is frozen, snow or ice aggregate roads can be built, permitting winter transportation of equipment and supplies.

4. Air

The constraint in this mode of transportation using fixed wing aircraft or helicopters is weather (visibility, wind, precipitation) and the availability of landing and takeoff strips (for fixed wing aircraft) which in winter could be built on ice, but in summer would require a substantial amount of sand and gravel.

Some other problems connected with offshore operations are discussed in Section V.E. of this report. Consideration of the various phases of operation would be a part of an Environmental Impact Statement or other documents usually prepared.

In addition to the known means of transportation, there are some advanced concepts now being studied and comments on these are presented in Section III.C.

III. CONCEPTS FOR FIELD DEVELOPMENT AND PRODUCTION

With the exception of a pilot program conducted by Panarctic in the Canadian Arctic Islands, there are at present no offshore oil or gas production wells in the Arctic. There is some relatable experience from the Union Monopod and other platforms located at Cook Inlet. However, the applicability of this experience is limited when related to the Beaufort Sea. There is also little actual experience with permanent artificial islands or other structures in Arctic waters. The lack of this should not imply that the necessary technology is unavailable. Industry has been performing conceptual studies for more than five years on field development approaches and on advanced designs of sand/gravel and ice islands, as well as fixed and mobile platforms for both exploratory drilling and production. Considerable design research and model testing has been conducted on them to prove the viability of these concepts. In addition, other segments of industry have been studying various means of bringing the oil/gas out of the Arctic. These advanced ideas, and the state of the technology necessary for their operation, will be addressed in this section.

In discussing production systems for oil/gas offshore, it is important to realize that a platform with its equipment is only part of the whole operation. There are additional problems: the transportation of the oil/gas pumped from a well to consumer centers; the logistics for personnel and spare parts for production facilities; the disposal of human and chemical waste; the need for potable water; etc. For a complete system assessment, all these functions must be examined for the hazards associated with the harsh Arctic conditions and for their potential impact on the environment.

In view of this, the offshore structure and some advanced oil transportation concepts will be addressed first, followed by a more detailed examination of hazards and impacts. A brief discussion on logistics support has already been presented in Section II. A more thorough assessment of a complete operation should be made after the location, preliminary design, and oil/gas transportation mode are determined.

Figure 3-1 shows a listing of several concepts being considered by the industry and a discussion of each item on this list will follow. It will be noted that some of the concepts may be used in both exploration and in field production, and selection of those most suitable is left to the operator.

Figure 3-1. Other Concepts

		APPLICATION
A. Fixed		
	• Artificial Islands with Caissons or Piles	E, D, P
	• Ice Islands (In Evaluation)	E, D, P
	• Ice Strengthened Islands (Water Frozen For Stability)	E, D, P
	• Barrier Islands	E, D, P
	• Diaphragm Islands (Periphery Made Of Rubber Diaphragm)	E
	• Tunneling	D, P
B. Mobile		
	• Grounded Barges	E, D, P
	• Monocones	E, D, P
	• Monopods	E, D, P
	• Ice Cutting Platforms	E
	• Air Cushion Vehicles	E
	• Big Buoy	E, D, P
C. Arctic Oil Transport		
	• Submarine and Semi-submarine Tankers (Deep Water Only)	P
	• Arctic Marine Locomotive	P
D. Supporting Element		
	• Subsea Completion	E, D, P

E - Exploration
D - Development
P - Production

A. FIXED SYSTEMS

1. Caisson-Retained Sand/Gravel Island

One of the concepts which has a permanency potential (i.e., sufficient lifetime for oil/gas reservoir depletion) is shown in Figure 3-2. This is a caisson-retained island proposed by Imperial Oil, Ltd. (de Jong, 1978). It consists of eight trapezoidally shaped steel caissons, each 43m (141 ft) long, 12m (40 ft) high with a base of 13m (43 ft). The space surrounded by the caissons is filled with sand and gravel of sufficient bearing strength to support the drilling and production equipment. The caissons are designed for a water depth of 9m (30 ft) and thus provide 3m (10 ft) free-board. This freeboard is increased to 7.6m (25 ft) by an ice and wave deflector. For deeper water locations, it is necessary to build an underwater berm to an elevation of 9m (30 ft) below sea level as a base for the caisson ring (Figure 3-2). To enhance the permanency of the island slope, protection of the berm against waves and ice keels by means of gabions or large sandbags could be considered.

A unique arrangement for caisson assembly was proposed by de Jong. Rather than have them rigidly joined, they are hinged together, as shown in Figure 3-3. Under ice loads, the caissons can shift slightly to conform to the contour of the frozen fill inside, thus assuring load-sharing between the caissons and the fill. The caissons are tied together

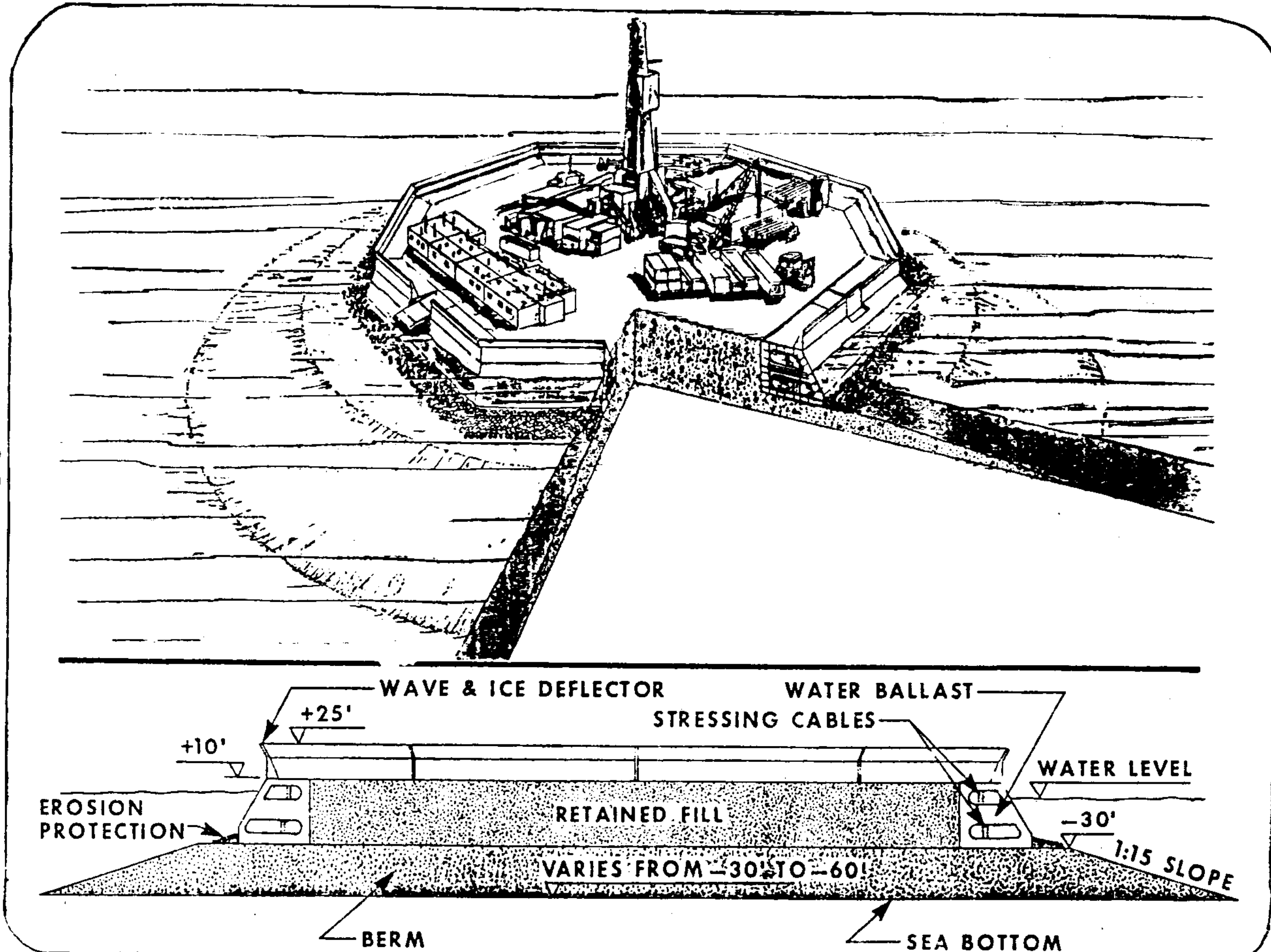


Figure 3-2. Caisson Retained Island, Imperial Oil (de Jong, 1978)

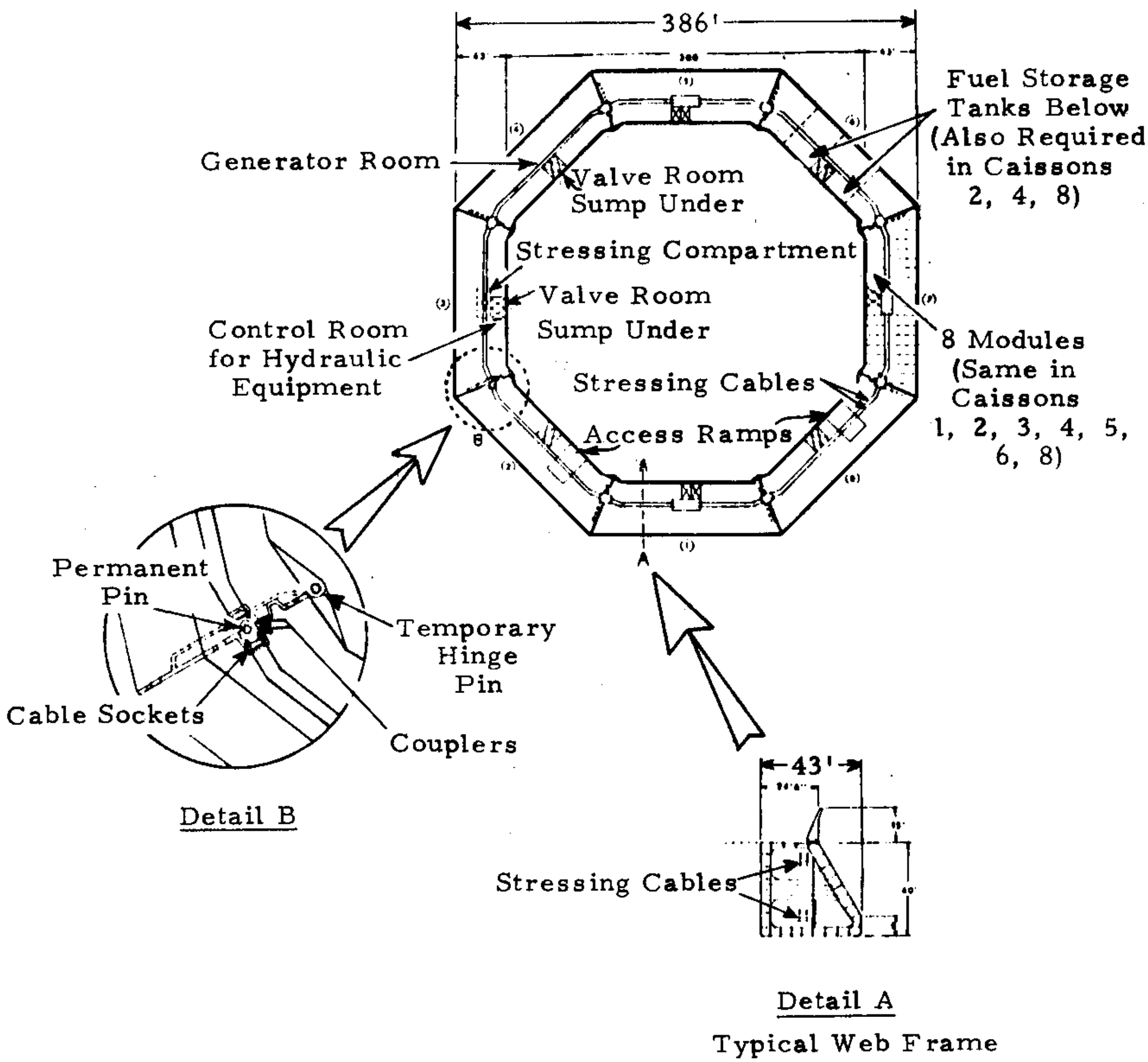


Figure 3-3. Caisson Retained Island, Simplified General Arrangement (de Jong, 1978)

in a ring by means of two sets of stressing cables.

The caissons, while deballasted, float in a stable position and can be towed either singly or in a rhombic configuration in sets of four joined together with temporary pins. Once in position, they are secured with permanent pins and stressing cables, then flooded with water and set on the seabed or berm. If a caisson-retained island is used for exploratory development, the caissons can be deballasted after a well is drilled and moved to another location.

One of the advantages claimed for a caisson-retained island is a saving in fill requirements when compared with other types of sand/gravel islands discussed before. This is shown in Table 3-1. It can be seen, for example, that in a water depth of 9m (30 ft), the caisson-retained island would require only 1/10 of the fill of a sacrificial beach island, and 1/3 of a sandbag-retained island.

The construction costs of a caisson-retained island in 9m (30 ft) of water is estimated at $27 million (de Jong, 1978). If the island is used for many years, maintenance and repair costs have to be added. Hydronamics (Stigter and Andreae, 1973) estimated the annual maintenance cost of a gravel island to be approximately 10 percent of construction cost.

The development status of this concept consists of a thorough design study utilizing Imperial Oil experience in the construction and operation of temporary artificial islands.

Table 3-1. Island Fill Requirements, Imperial Oil (de Jong, 1978)

WATER DEPTH	SACRIFICIAL BEACH ISLAND	RETAINED FILL ISLAND (SANDBAGS)	CAISSON RETAINED ISLAND 30' SET DOWN DEPTH
	CU YDS	CU YDS	CU YDS
20'	800,000	250,000	150,000
30'	1,700,000	500,000	150,000
40'	2,500,000	900,000	300,000
60'	5,000,000	2,500,000	900,000

2. Double Cone Ice Island

Thermo-Dynamics, Inc. proposed a Double Cone Ice Island, shown in Figure 3-4, for water depths up to 70 feet. The design consists of an internal array of 12m (40 ft) diameter steel tubes. Six of the tubes extend from the bottom to near the top of the 62.5m (205 ft) tall structure, and other shorter tubes surround the long ones to form the lower cone. The tubular structure is covered with a shell of sheet steel. The purpose of the lower cone is to break up ice; the upper cone serves to deflect ice and waves from the deck which has a diameter of 67m (220 ft).

The complete structure can be towed to a location, and the tubes ballasted with water to set them on the seabed. The water in the tubes is then frozen by on-board refrigeration equipment to provide lateral rigidity against ice forces.

Four of the tubes adjacent to the central tube each contain 2.5m (8 ft) diameter drilling columns. Eight wells could be drilled from each column with a total of 32 wells (Oil and Gas Journal, 1970). The designer estimated the cost of the 16,000 ton structure at $40 million (1970 dollars), with two years construction time. Preliminary design of this concept was proposed several years ago and no further work on it has since been done.

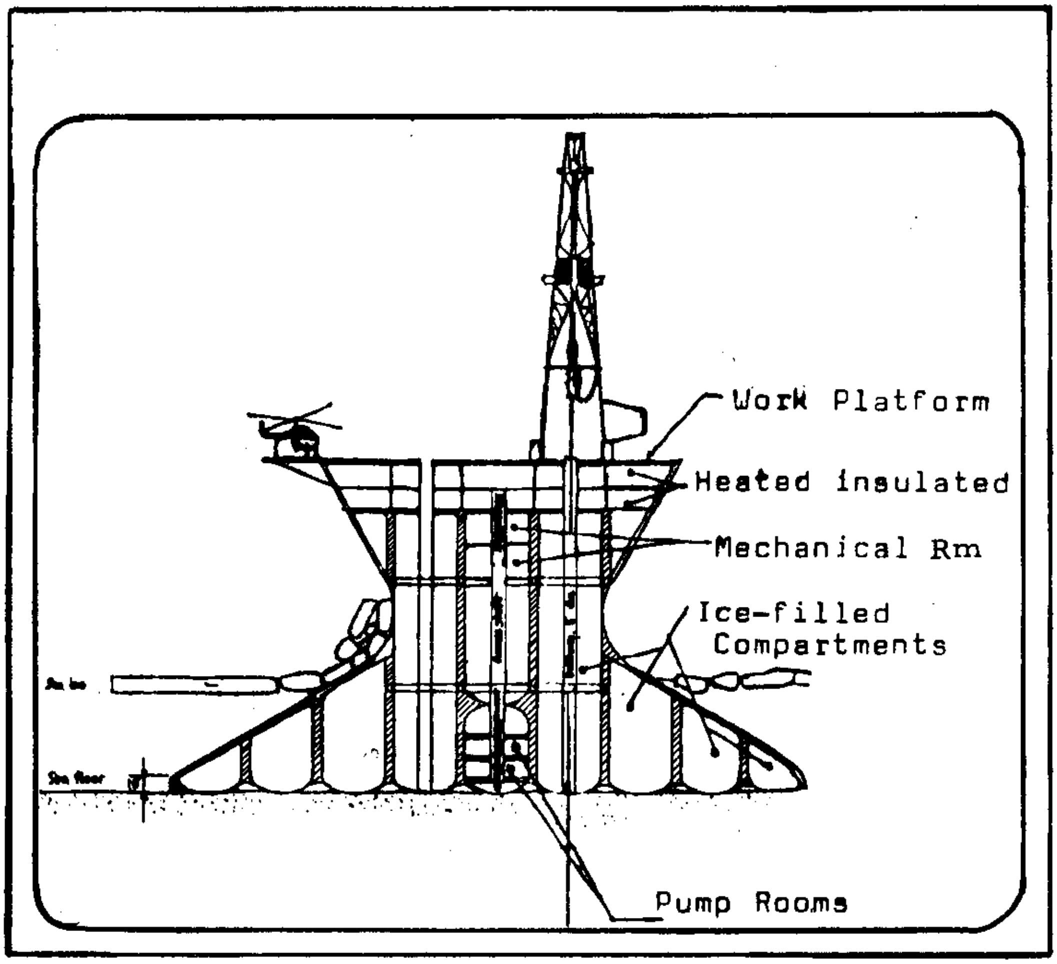


Figure 3-4. Double Cone Ice Island Cross Section (Oil & Gas Journal, 1970)

3. <u>Cellular-Sheet Pile Island</u>

A cellular-sheet pile island was proposed by Forssen Engineers (Forssen, 1975) and is shown in Figure 3-5. Two versions of the island were considered; a small one for exploratory development, and a larger one for development and production.

The smaller island (shown in Figure 3-5) consists of four steel caissons 23m (75 ft) in diameter driven into the seabed and then ballasted with well-graded fill material. This material must be frozen after placement, using refrigeration equipment if necessary. After the four caissons are set, a smooth, round sheet bulkhead is placed around the caissons, forming an island 60m (200 ft) in diameter. The space between caissons and the bulkhead is filled with sand or gravel which is frozen to provide the required resistance against ice forces. The 60m (200 ft) diameter was considered as the minimum acceptable to resist overturning, sliding and internal shear failure (Forssen, 1975). It was estimated that the construction of the island would take 40-50 days, assuming that the structural material was stored nearby.

The larger island is designed on the same principle except that it consists of 15 caissons with a sheet bulkhead diameter of 150m (490 ft). Two seasons would be required to build such an island.

The esimated cost of the small island (in 1975) was $6 million, and the larger one $20 million.

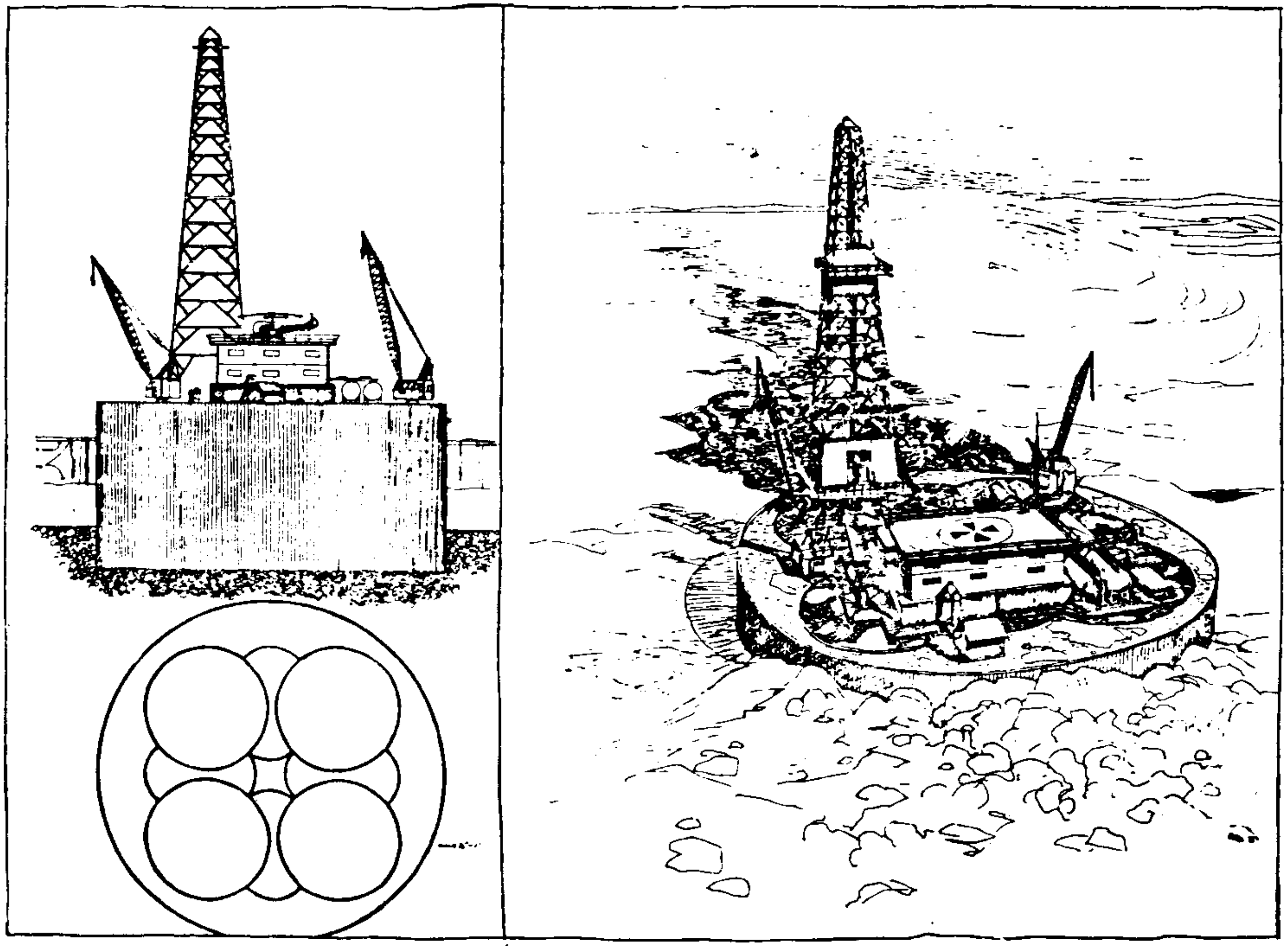


Figure 3-5. Cellular-sheet Pile Island (Forssen, 1975)

A preliminary design of this concept was presented a few years ago, and no further work on it has been done.

4. Permanent Ice Platform

It appears to be a paradox to discuss a permanent ice platform, yet past observations indicate that if an ice mass is large enough, it could survive for years in the Beaufort Sea environment. An example is the T3 (Fletcher) island still in existence, which was used for several years as a weather station in the Arctic pack zone.

At present, Exxon is building an experimental grounded ice platform north of Prudhoe Bay in 3m (10 ft) water depth. The platform is built using various water flooding techniques. According to the plan, the ice will be thickened to a total of 9m (30 ft) in the center, tapering toward a circular periphery of 366m (1,200 ft) diameter. The objective of this experiment is the evaluation of construction techniques, ice growth rates, and survival during the spring-summer season. The experiment was estimated to cost $1.6 million. Once the platform survives one season, it will probably withstand the following seasons provided that ice is added to make up for the summer losses. The future application of this concept will depend on the outcome of the Exxon experiment. If the platform does not survive the spring and summer seasons, it would still contribute to the technology of a one season ice platform.

5. Barrier Island

There are three chains of curvilinear islands resembling a barrier off the Beaufort Sea Coast. The eastern chain extends from Brownlow Point to Reindeer Island; the central chain from Point McIntyre to Thetis Island; and the western chain from Cape Simpson to Point Barrow. Typically, the islands range from 90 to 110m (300 to 360 ft) in width, but some are as wide as 450m (1,500 ft). The islands may be as long as 9 km (5.6 mi) with a height less than 3m (10 ft) above the sea level (Barnes et al, 1978). Exploratory or stratigraphic wells were drilled in the past by operators on the Flaxman, Reindeer and Tigvariak islands. Some of the barrier islands could be considered for production platforms.

Certain of these islands are feeding and habitat grounds for several bird species. For instance, Cross and Howe Islands are critical nesting habitats for birds, and have been nominated as ecological reserves. Duck, Niakuk and western Cooper Island are also heavily-used by nesting birds. It has been recommended that industrial activities be banned on these islands (Hopkins et al, 1978).

The barrier islands often have very low freeboard (Hanson, 1978). Consequently, an increase in the freeboard would be necessary to prevent ice intrusions. Consideration must be given to both the prevention of beach erosion by natural wave and current action which is causing island migration at the rate of 13 to 30m (43 to 98 ft) westward, and from

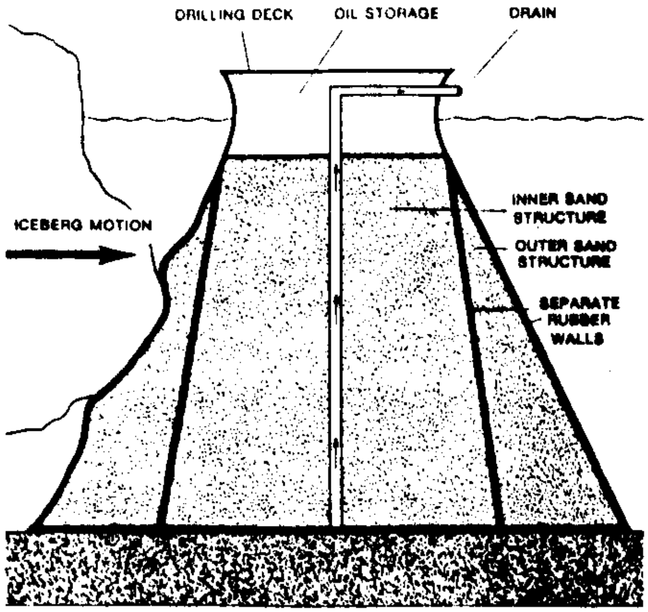
3 to 7m (10 to 23 ft) landward each year.

This is a viable concept, and any problems related to it are environmental, not technological, and merely require local ecological studies.

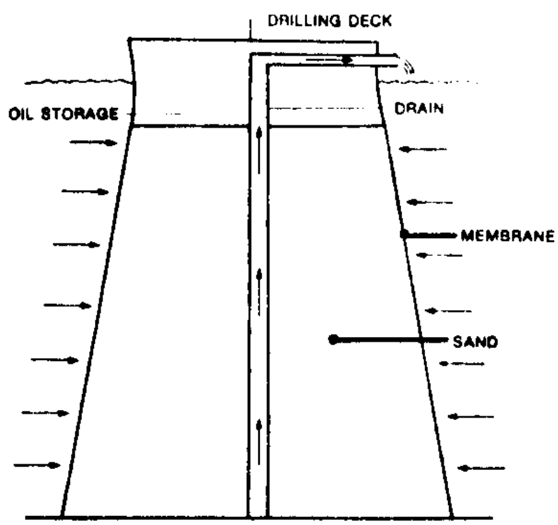
6. <u>The Diaphragm-Sand Island</u>

The diaphragm-sand island shown in Figure 3-6 was conceived and designed by Golder Associates, Ltd., in Great Britain jointly with supporting contractors. The concept is based on the geotechnical principle that the lateral pressure exerted by sand (which is dewatered) is equal to about half of the water hydrostatic pressure at a given depth. Consequently, when a membrane is filled with sand and surrounded by water, there will be a net compressive pressure on the membrane ensuring its stability. Conversely, if the sand becomes saturated (i.e., through either leakage or longer-term moisture migration) the hydrostatic pressures would equal, and a net outward (tensile) pressure generated by the sand weight may ultimately develop.

Model tests were performed to prove this principle and in September, 1976, a prototype, shown schematically in the bottom of Figure 3-6, was installed in 16m (52 ft) of water in Christchurch Bay, England, with approximately an 8m (26 ft) deck diameter. The wall of the diaphragm was made of panels of high strength nylon fabric coated on both sides with a high abrasion resistant polychloropene rubber. The panels



DIAPHRAGM ISLAND UNDER ICE LOAD



GEOTECHNICAL PRINCIPLES OF DIAPHRAGM ISLAND. THE LATERAL PRESSURE OF SAND IS HALF OF THE CONFINING HYDROSTATIC PRESSURE.

Figure 3-6. Diaphragm Island (Ocean Industry, 1976) were bonded by a vulcanizing process. The sand was continually dewatered by pumping during the filling operation and by smaller, permanently installed pumps after the construction was completed. The sand was stable and could support loads equal to 75 percent of its weight (Ocean Industry, 1976). Unfortunately, after the island was constructed its freeboard must have been insufficient because a storm which developed in that location destroyed it.

For Arctic application, the designers envisage a double diaphragm configuration shown on the top of Figure 3-6. The outer membrane would deform from ice pressure, thus absorbing ice energy while the inner structure membrane would remain undeformed.

The feasibility of the concept for Arctic offshore is doubtful because of the large ice forces which might not be contained by a deformation of a diaphragm and sand. Puncture of the diaphragm by ice could result in a catastrophic failure.

7. The Tunneling System

An offshore tunneling and chamber system (OTACS), shown in Figure 3-7, was proposed by Lewis et al (1977). For a reservoir of 30 square miles, a 10-mile tunnel was proposed with eight drilling chambers 1.25 miles apart. With 12 wells per chamber, the 96 wells would be adequate for field development. The upper 1,000m (3,300 ft) of sediment in the Beaufort shelf is probably unconsolidated; therefore, the tunnel would

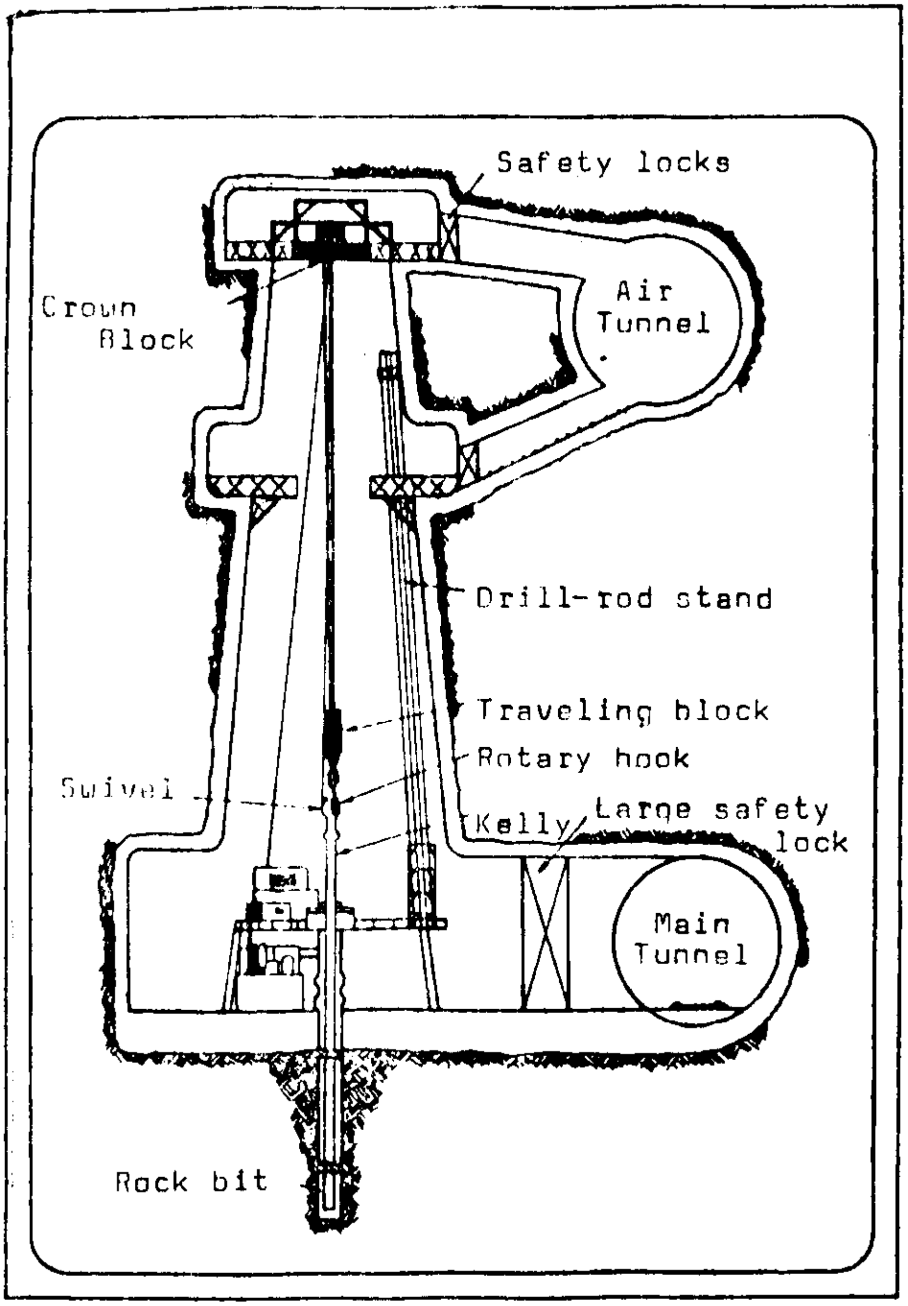


Figure 3-7. Drilling Chamber in a Tunnel Concept (Lewis et al., 1977)

presumably require lining to support the overburden. The OTACS would consist of two tunnels: one for the drilling supplies, flow lines, auxiliary equipment, etc., and the other one for inflowing fresh air and an emergency exit. Various safety devices and personnel safety measures were proposed, not unlike those employed in submarines. The tunnels would be at a preferred depth of 600m (2,000 ft) and it was estimated that the project would take 4.2 years to complete with a six-year cost estimated at $1.6 billion (in 1975 dollars).

The following advantages were quoted for the tunnel concept: (1) onshore drilling equipment could be used; (2) required hydrostatic pressure of the drilling mud would be reduced, thus decreasing the hazard of the geologic formation failure; (3) weather would not affect year-round drilling operations; (4) large storage capacity for oil would be available; and (5) oil spills would be easier to control and would not affect the environment.

The tunnel concept was studied by R&D Associates as part of a proposal effort. A substantial amount of technical and cost data were accumulated at that time. To the best of our knowledge, however, no further work has since been performed. Although not stated in the tunnel study, there would be a safety hazard to personnel in case of a well blow-out which would be difficult to mitigate.

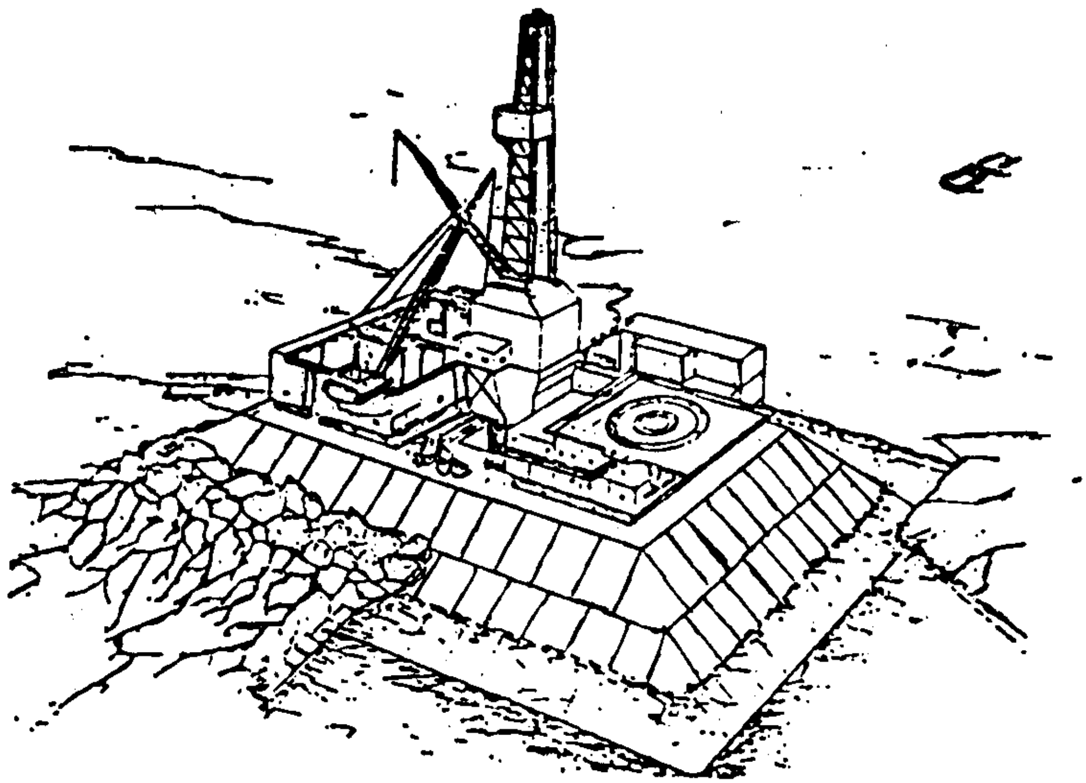
B. MOBILE SYSTEMS

1. Grounded Barges

In the discussion of exploratory drilling concepts (Section II A.4), mention was made of two grounded rail barges joined by superstructure and used by Sun Oil, Ltd. There is no reason why barges built specifically for that purpose with reinforced hull and sufficient deck area could not be used as production platforms in shallow waters of the Beaufort or Chukchi Seas.

Figure 3-8 shows such a concept proposed by the Offshore Company. The size of the upper deck indicated on Figure 3-8 is for exploratory drilling application. For production, the upper deck size would need to be increased to at least 61 x 91m (200 x 300 ft), assuming that some of the processing equipment could be installed on shore. The barge could be protected against wave erosion and ice invasion by a strengthened hull, or by using sand and gravel overlain by gabions or concrete blocks.

It appears that no work beyond the preliminary design stage was done on this concept by the Offshore Company. However, this approach uses elements of proven technology (barges, slope protection) and should be rated as equal in its feasibility to reinforced artificial islands.



OPERATING W. D. : 6' MINIMUM
30' MAXIMUM

HULL DIMENS. : 288' X 308' LOWER
120' X 200' UPPER
36' DEPTH
6' ADDITIONAL POSTED HEIGHT

Figure 3-8. Grounded Barge Island (Hudson, 1978)

2. Monocones

Monocone concepts have been studied by several operators, including Imperial Oil, Ltd., Exxon and Dome. A double-cone design has been investigated by Chevron Research Company. The principle of the concept is to expose a conical surface to the invading ice so that it is broken up by flexure rather than by crushing, thus reducing ice forces.

The Imperial monocone design is shown in Figure 3-9. The unit consists of three parts: a steel platform with superstructure, a circular concrete hull with a concrete column, and a steel conical collar which consists of two halves frictionally clamped at the desired level. The elevation of the collar can be varied by controlled water ballasting (Jazrawi et al, 1977). The wells would be drilled through the central column.

The hull, when unballasted, has a draft of 10m (33 ft) and can be towed to a location in the Beaufort Sea from the west coast during the summer months. Once in position, the hull compartments are ballasted to allow a level setting on the seabed. Some difficulty with the stability of the hull was experienced during model tests of the set-down procedure at the Ship Laboratory In Ottawa, Canada (Jazrawi et al, 1977).

The monocone was designed for a maximum water depth of 41m (134 ft) and a minimum water depth of 16.8m (55 ft). Consequently, its application to tracts within the 20m (∿66 ft)

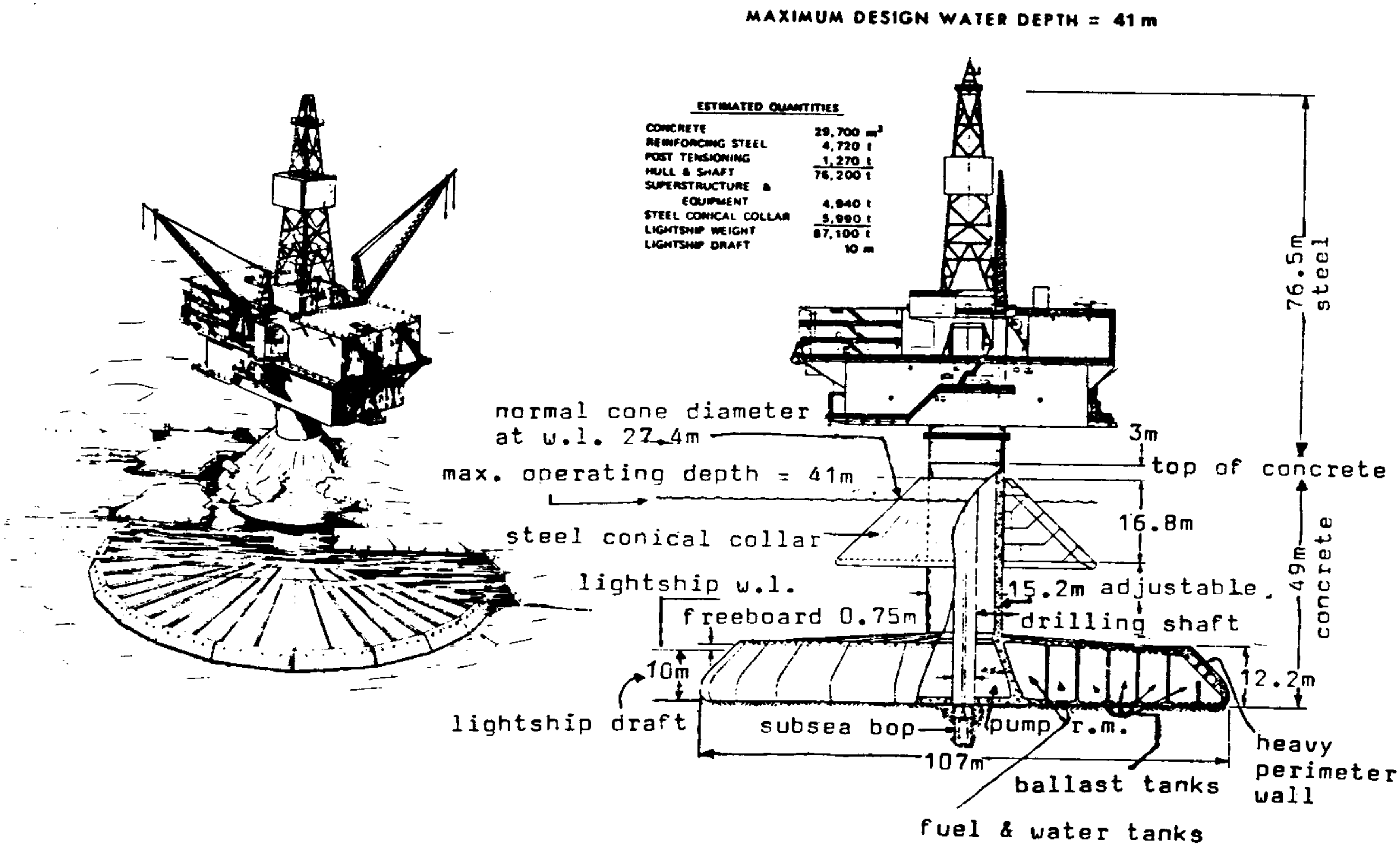
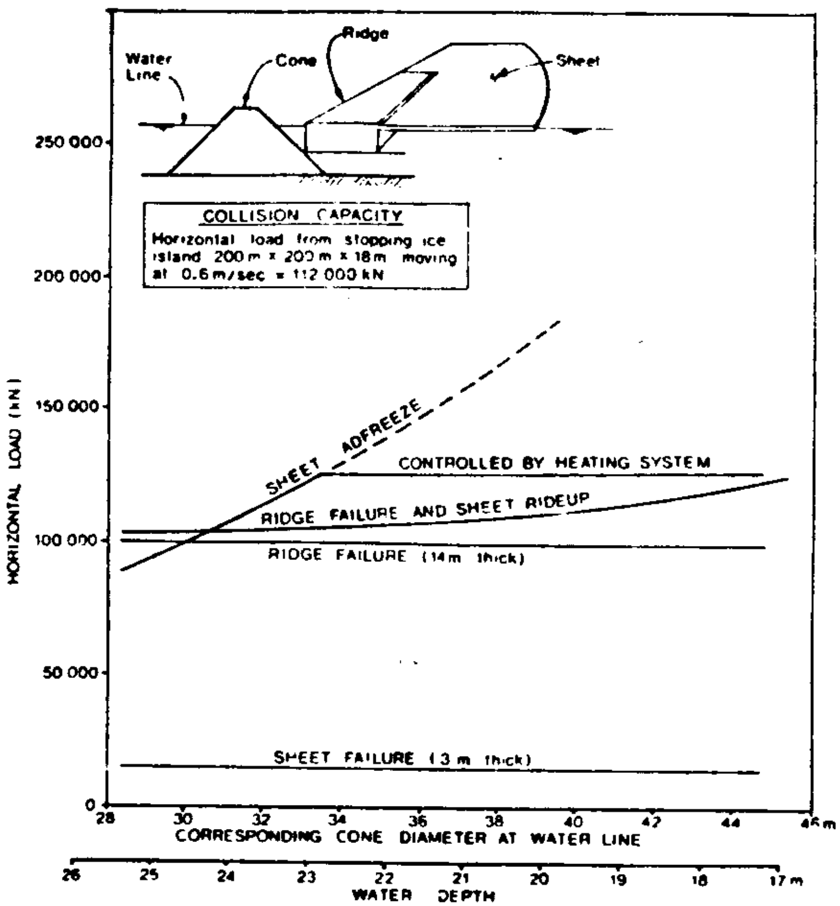


Figure 3-9. Monocone Drilling Rig 41, Imperial Oil, Ltd. (Jazrawi et al., 1977)

isobath would be marginal. The freeboard from maximum water level to the top of the triple deck is 15.2m (50 ft), and the deck length is approximately 60m (200 ft). Other dimensions are shown in Figure 3-10. Note also the position of the BOP below the mudline for exploratory drilling. For production operation, additional anchoring of the hull by piles could be considered.

Since the nominal diameter of the cone is 27.4m (90 ft), a large area is exposed to ice pressure, and the control of adfreeze forces is an important design consideration. Figure 3-10 illustrates the predicted increase in ice forces with adfreeze as compared to point contact forces of a 3m (10 ft) ice sheet, or 14m (46 ft) ice ridge. To avoid adfreeze, Imperial proposed heating the cone surface with waste heat and additional heaters. The angle of the cone is important and Croasdale (1977) reported that for angles (from horizontal) greater than 45^{o}, the ice forces start to increase significantly. Danys and Bercha (1975) observed that for a 75^{o} cone the ice failed in crushing. Chevron and the Offshore Company (Hudson, 1978) have proposed a similar design, also utilizing a heated cone surface. Practical design limitations in accommodating larger ice masses at varying load rates would appear to place certain restrictions on this concept where major ice ridges or blocks are anticipated.

The cost of a monocone structure is estimated at $50 to $80 million (Hudson, 1978) which is not much greater than the



HORIZONTAL ICE LOADS
45° CONE

SHEET RIDE-UP ON MODEL

Figure 3-10. (Jazrawi et al., 1977)

cost of a conventional drilling platform, but the operational and maintenance costs in the Arctic will be substantially higher than in milder climates.

The design criteria for monocones (or monopods described below) should in many respects be similar to the rules for submersible botton-founded structures such as those issued by Det Norske Veritas of Norway. In addition, more detailed guides for ice force calculation are needed. For Beaufort Sea structures, ice forces will be the principal design parameter determining the required structure strength and rigidity. Existing rules and regulations (i.e., Det Norske Veritas, API RP 2A, USGS OCS Orders) do not deal adequately with the ice problem and need appropriate revisions to guide the designers. API committee is working at present on separate requirements for design of structures in the Arctic environment.

It is not within the scope of this report to define design criteria or regulations for ice forces, but some discussion on the ice forces and their effect on structures will be presented in Section IV.A.

The status of monocone development comprises preliminary design, design analysis, and model tests performed by Imperial Oil (Jazrawi et al, 1977) and others. Model tests consisted of ice force measurements in a large outdoor test based at Imperial's facility in Calgary, and stability and deployment tests at 1/60 scale conducted in the Marine Dynamics and Ship

Laboratory of the National Research Council in Ottawa. Data obtained in these tests were used in the preliminary design. The need for some improvements in stability during the deployment of the monocone was also indicated from the model tests.

3. <u>Monopod</u>

The monopod concept is not new. One monopod was built by the Marathon and Union Oil Companies in 70 feet of water in Cook Inlet in 1966. All wells were contained within the column and the hull was attached to the seafloor by pilings driven through it (Hudson, 1978). However, this monopod was designed for considerably lower ice loads than those estimated for the Beaufort Sea (Brown, 1976).

A monopod design for exploration drilling in the Arctic offshore was proposed by Imperial Oil, Ltd., and is shown in Figure 3-11. The maximum design water depth is 12m (40 ft) and the minimum depth is approximately 3m (10 ft). The structure is made of steel and consists of three parts: the hull, the column, and the superstructure, and weighs 15,000 tons. The circular hull is protected against ice floes during towing operation by a 1.5m (5 ft) thick concrete ring which also acts as a permanent ballast for increased stability. Once on location, the hull is ballasted with water and set down in a prepared excavation in the seabed so that the hull is totally concealed and only the relatively slender column

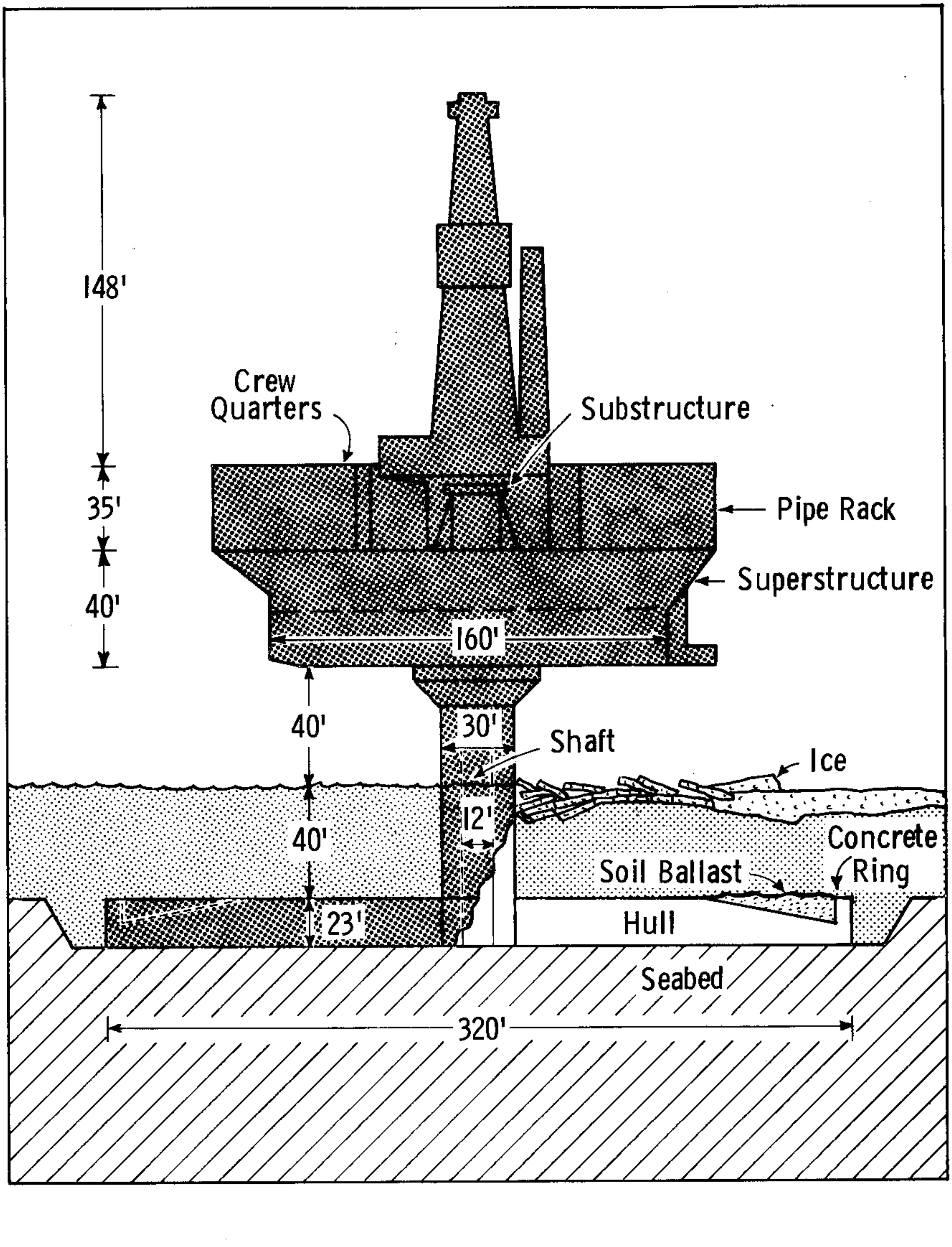


Figure 3-11. Monopod Drilling Unit (Brown, 1976)

is exposed to ice loading (Brown, 1976). To safeguard against ice scouring, a deeper burial of the hull may be considered for a permanent installation. The deck as designed for exploratory drilling is rectangular, 24 x 48m (80 x 160 ft), but for field development and production the deck size would have to be increased. The exploration unit could be moved to another location by breaking bottom soil suction with a jetting system and by hull deballasting. The entire operation should take about three days (Brown, 1976).

The rig would have a subsea BOP for exploratory drilling. For field production, increasing the size of the shaft drilling tunnel and providing additional means of anchoring of the hull by piles could be considered.

The monopod was designed by Imperial Oil for operation in landfast ice based on four-year large scale "nut cracker" experiments in the Arctic and in Alberta. These measurements of ice crushing strength determined that the lateral ice force was 100×10^6 N (22.5×10^6 lb). Also, the experience on the Marathon-Union Oil monopod installed in the Cook Inlet in 1966 was utilized in the preliminary design.

4. Ice Cutters

The Sedco and Sea-Log Company proposed a monopod ice-cutting concept shown in Figure 3-12. The proposed drilling platform as shown is semi-submersible with a 12m (38 ft) diameter column. There is a rotating circular toothed collar

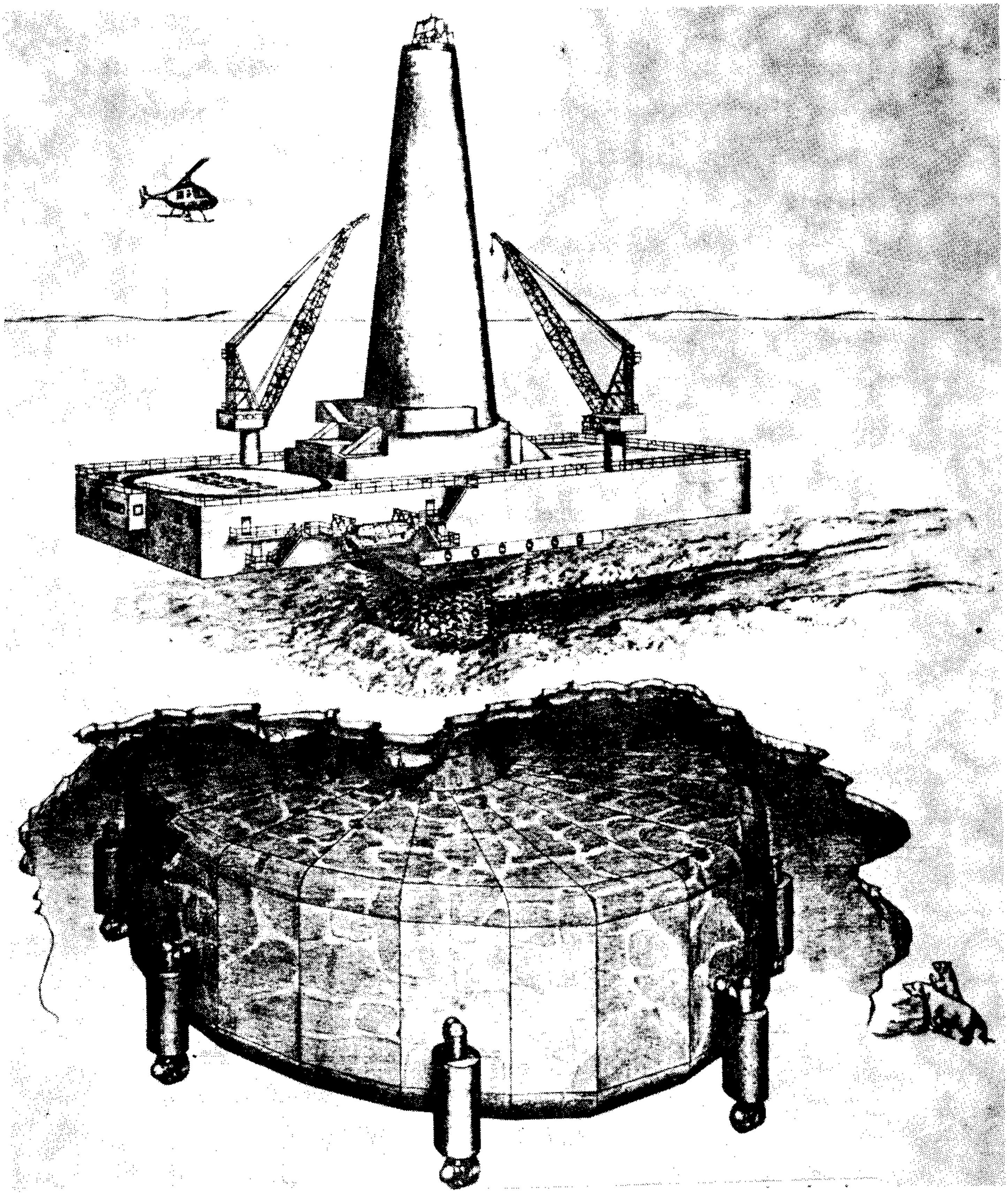


Figure 3-12. Sea-Log Ice Cutter (Sea-Log Publication)

around it to cut the ice as it moves past the platform. The steel teeth on the cutting collar extend 1.4 to 1.8m (4.5 to 6 ft).

Laboratory tests and scale model tests with a 0.85m (2.8 ft) diameter ice cutting cylinder were carried out in Resolute Bay in Canada (McIntyre, 1975). The objective was to study the feasibility of the concept and to provide data on horsepower requirements as a function of ice thickness and rate of movement.

It is doubtful that this technique would be adaptable to the shallow waters of the Beaufort Sea, as conceived. It would probably be necessary to adopt the monopod grounded hull configuration and limit the operation to landfast ice in the winter season when the rate of ice movement is relatively low. There are also questions regarding the reliability of the exposed rotating cutters under the rigorous conditions of the Arctic Sea.

5. Air Cushion Vehicles

Air cushion vehicles (ACV's), both self-propelled and nonself-propelled, have been under development for a number of years in various countries, notably in France, Canada and the United States. Most of the research and development work on ACV's for Arctic application was done in Canada. Here, the ACV was evaluated as an air cushion barge towed by a tracked or wheeled vehicle, moving by self-winching with cables attached to deadman anchors. It has also been tested as an icebreaker, utilizing the air blown from under the skirt to displace water from below the ice, causing ice to break from its own weight (Snyder, 1977). A technical paper by Turner et al (1972) contains an example of this technique. In this instance, an air cushion barge ACT-100 (100-ton payload) was tested on ice in a back bay, near Yellowknife, in N.W.T., Canada.

One of the advantages of an air cusion barge is its ability (with a self-winching propulsion) to cross rugged ice-covered areas of water in the winter, or melted soggy tundra in spring or summer.

In the concept proposed by Global Marine, the Air Condition Drilling System (ACDS) consists of two air cushion barges, one to transport the drill rig and the other to carry personnel accommodations and supplies. The second barge could also serve as a standby unit if the first became disabled. The ACDS barge can carry a maximum payload of 1,200 metric tons (1,340 short tons) with deck dimensions of 69 x 52m (227 x 170 ft) and a ground clearance of 2.4m (8 ft). The all-up weight of an air cushion barge would be 2,840 metric tons (3,100 short tons).

The ACDS could be shipped in a fully-equipped condition by sea on marine barges. Then, when the ice is sufficiently thick, it could be towed by tracked vehicles to the drilling location, as shown in Figure 3-13. Once on location, the ACDS could be set on water after the ice was removed and moored

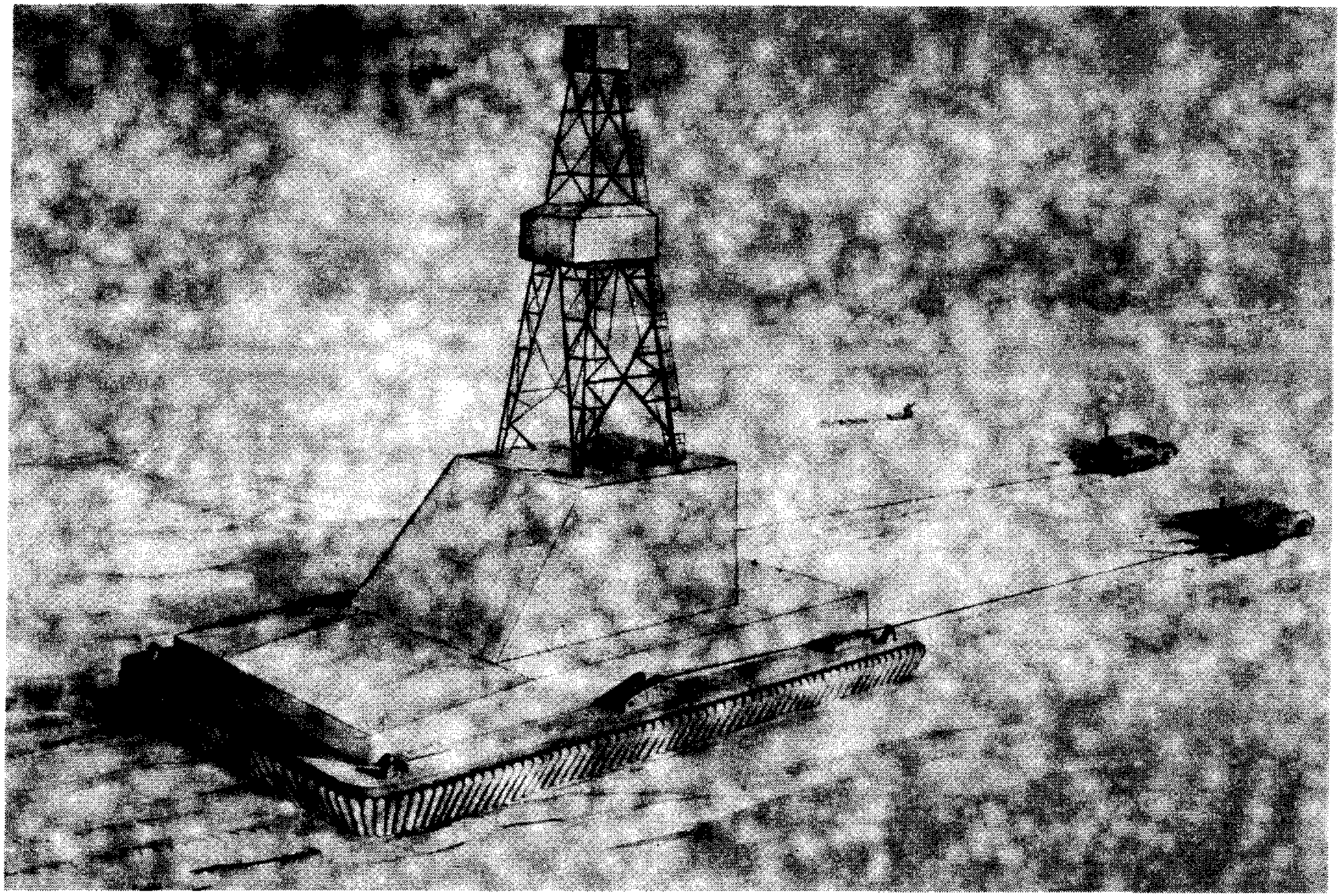


Figure 3-13. Air Cushion Drilling Vehicle in Transit (Global Marine)

either to the sea bottom or to the ice. Waste heat generated by equipment aboard the ACDS, together with some additional heat transferred to the sea water, is estimated to be sufficient to keep the immediate vicinity of the ACDS free of ice, as shown in Figure 3-14. It is postulated that if the rate or extent of ice movement is small, the ACDS would be able to remain on location and either melt the incoming ice or remove it by mechanical means (excavation from the moat area). In case of larger ice movements, the mooring and riser are quickly disconnected, the sea bottom BOP and subsea safety valves are shut, and the ACDS would move off location, either floating on water or on its cushion of air. Once the drilling hole is re-established, the ACDS would be winched or towed back to location and drilling could then be resumed.

An alternative way of drilling is through ice, assuming that the ice is thick enough to support the ACDS. This is shown in Figure 3-15. In this case, the ACDS could either move with the ice or rely on its ability to hover above the ice surface with the riser disconnected in the event of a larger-than-allowed ice movement.

The status of ACV development is not clear. Of the two types of ACV's, non-propelled units (air cushion barges) and self-propelled units, the latter have been developed and are being used as passenger transport units (i.e., across the English Channel and off the Southern Coast of France). The U.S. Navy has also built propelled ACV's in the 100-ton class

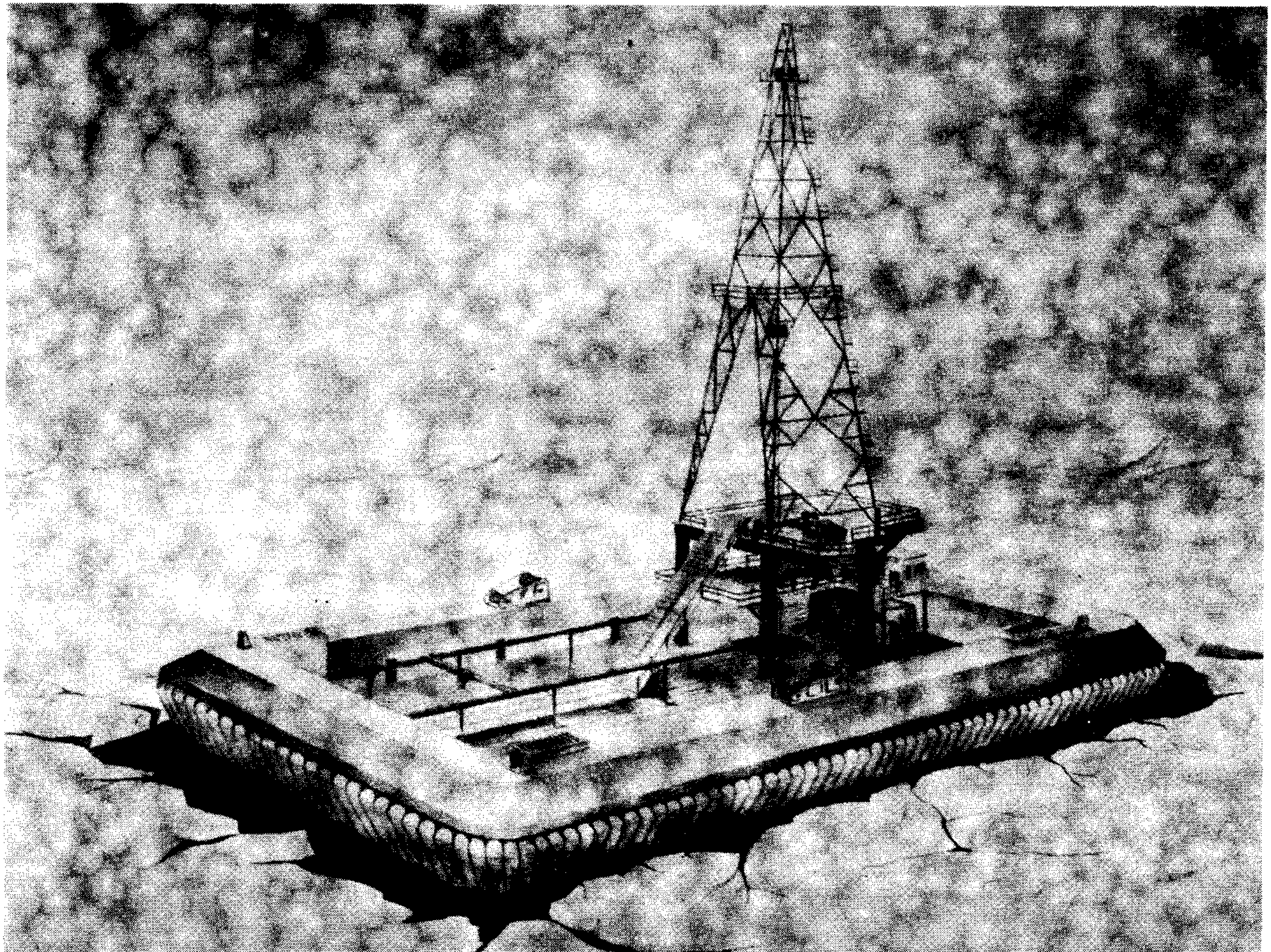


Figure 5-14. Air Cushion Drilling System (Global Marine)

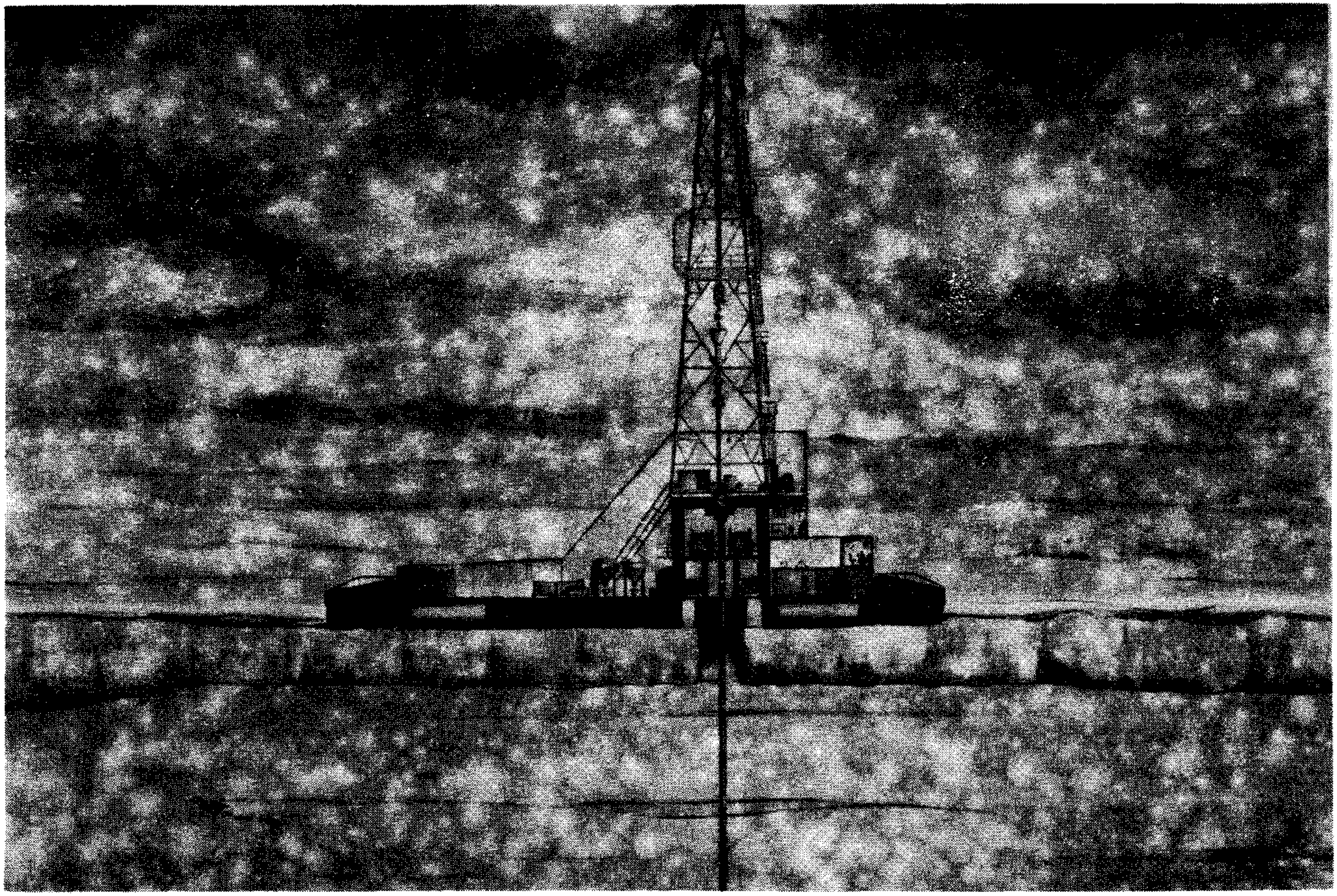


Figure 3-15. Drilling Through Ice From Air Cushion Vehicle (Global Marine)

as high speed vehicles for military application.

The air cushion barges (ACT 100) were used and tested by the Canadians in North Canada as freight carriers and as ice-breakers. The United States' experience with such barges was not very successful because of their inability to pass over 2m (7 ft) high river banks. This is, of course, a function of the size of a barge and the height of its skirt.

Global Marine Development Inc. has done detailed design analysis of ACV's used as drilling platforms, but results of their work are at present proprietary.

In summary, ACV's appear to offer a variety of applications for Beaufort Sea oil exploration both in the non-propelled and self-propelled versions. The concept warrants a comprehensive study of technology, operation and economics to determine the need for, and kind of, further development.

6. Big Buoy

The Big Buoy is a semi-submersible proposed by the Trosvik Group of Norway (Figure 3-16). It is estimated that its main propulsion of four units totalling 60,000 hp will enable it to operate at speeds of 2.5 knots in ice thickness of 2m (6.6 ft). Big Buoy is dynamically positioned while drilling. It is intended for operation in deeper waters (greater than 50m (164 ft). Consequently, the present design will not be suitable for shallow waters.

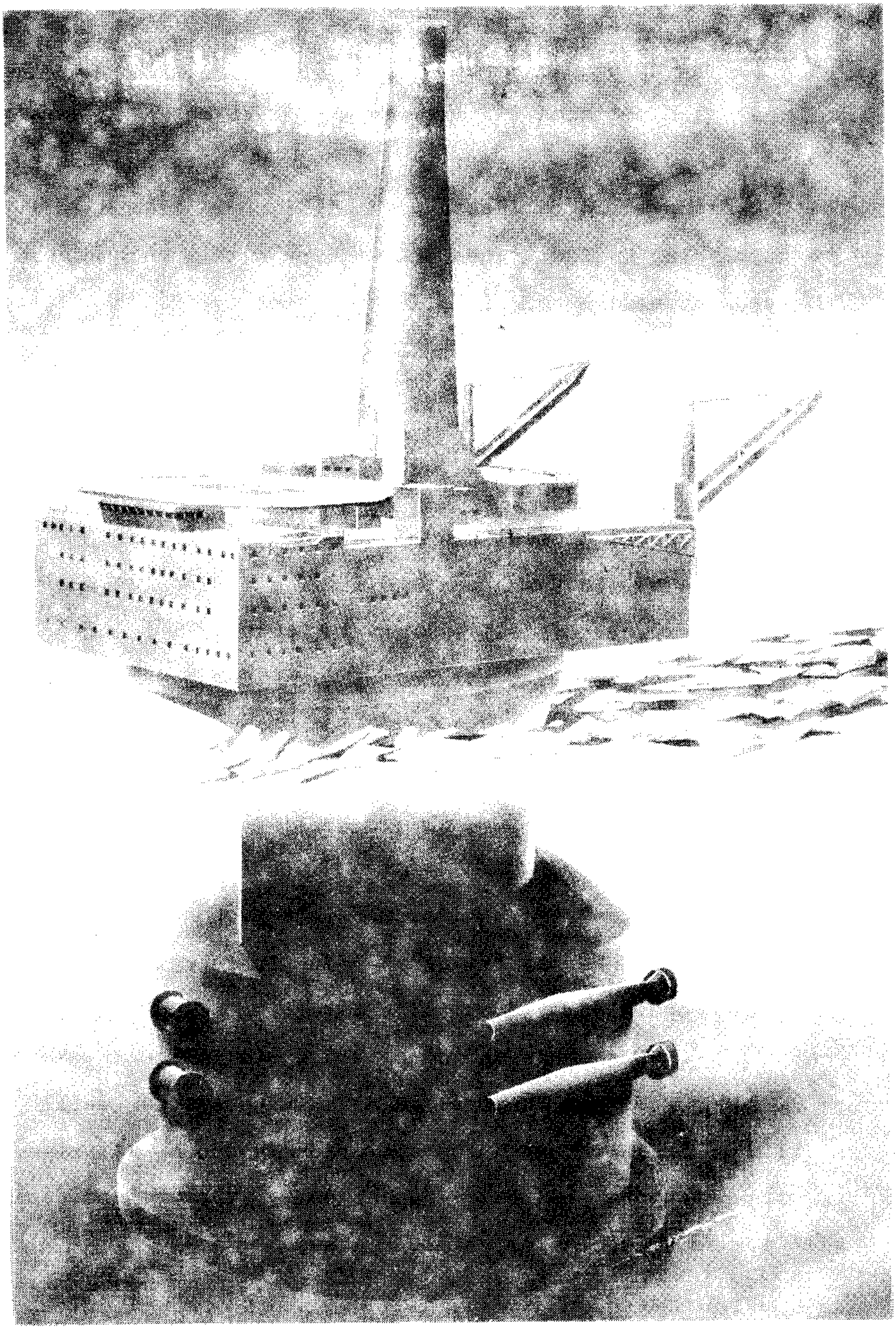


Figure 3-16. Big Buoy (Trosvik Publication)

The Trosvik Group has performed extensive model stability tests in a water tunnel, and detailed icebreaking model tests on the hull configuration were performed at the Wartsila ice laboratory in Helsinki, Finland.

7. Summary

To summarize the discussion on current and advanced drilling concepts, Figure 3-17 is presented. The figure illustrates the most viable techniques for Beaufort Sea offshore oil/gas development and it also indicates water depth range applicable to the approaches shown.

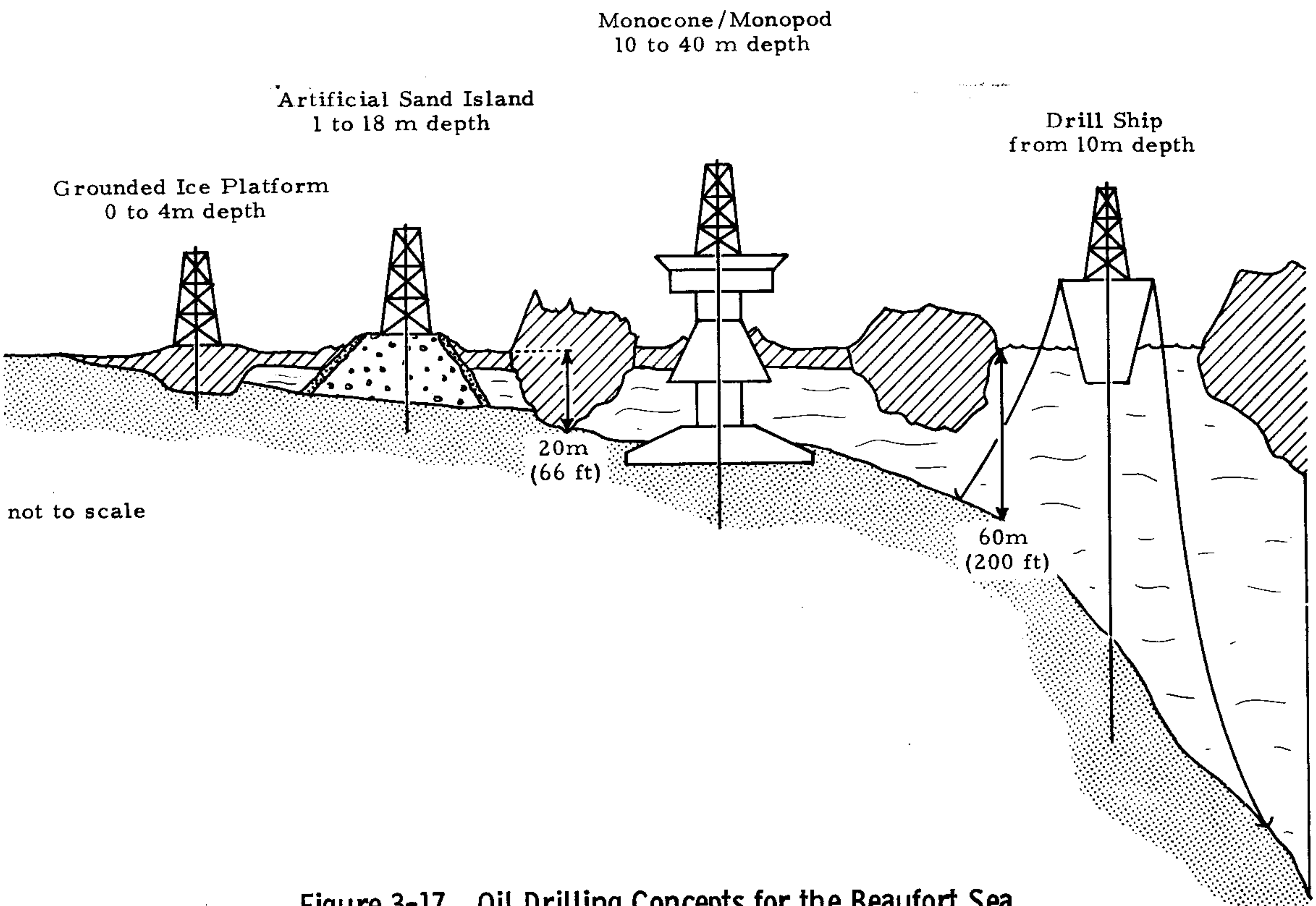


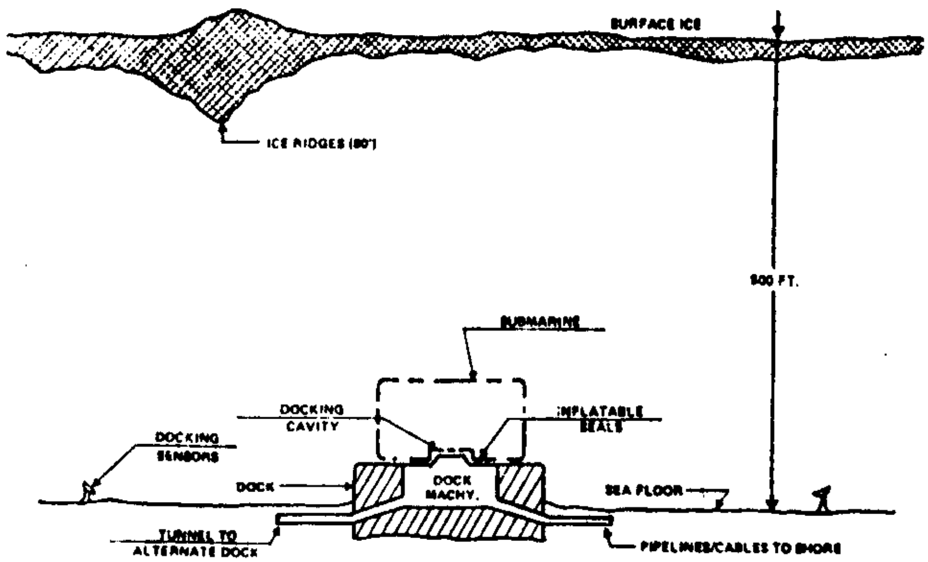
Figure 3-17. Oil Drilling Concepts for the Beaufort Sea

C. ARCTIC OIL TRANSPORT

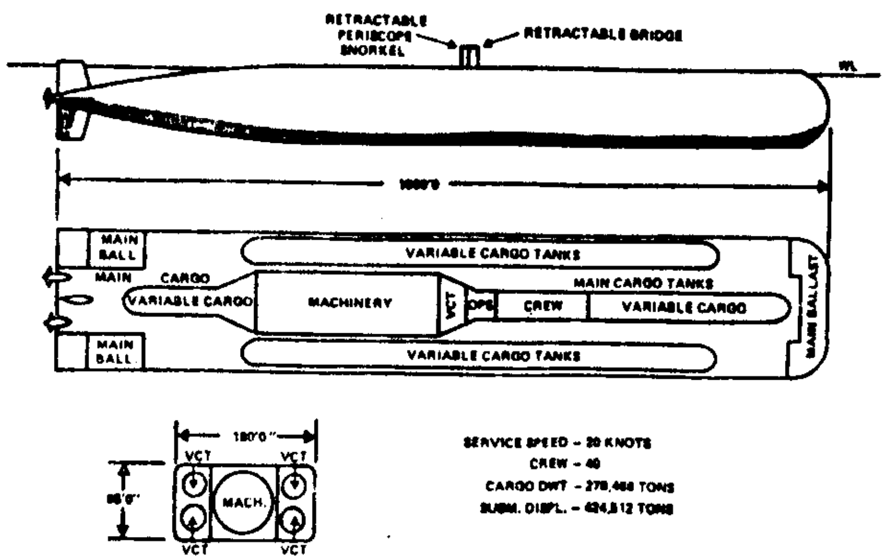
1. Arctic Submarine Tanker System

This concept was proposed by Taylor and Montgomery (1977) and is shown in Figure 3-18. Here, the tanker hull had a rectangular form for shallow water operation with a draft of 28 feet. The submarine propulsion was nuclear and consisted of one 120,000 SHP plant. The cargo tanks had a capacity of 2-million barrels of oil, and the ship would cruise at 20 knots in 213m (700 ft) water depth to avoid the hazard of an iceberg or ice island encounter. The objective of the submarine tanker was to carry oil from offshore Prudhoe Bay, or Ellef Ringnes Island in Canada and to the east coast refineries of the Virginia Capes. Two base routes were considered, one in which the submarine tanker traveled the entire route, and the other where it operated only in ice-covered northern waters, transshipping the cargo to surface tankers at Norway. The oil was loaded at a submarine undersea loading dock with pipelines for oil, electric power and communication transmission from onshore facilities. The undersea dock, also shown in Figure 3-18, could be fabricated in the continental United States and towed to its Arctic location.

Cost comparison between the tanker and Trans-Alaska pipeline indicated that the submarine cost using the direct route was 80 percent of the Trans-Alaska cost proposed for oil and 60 percent of the Trans-Alaska for the via-Norway route.



SEA-BOTTOM DOCKING



SUBMARINE TANKER CONFIGURATION

Figure 3-18. (Taylor & Montgomery, 1977)

The submarine tanker is not applicable to the Beaufort Sea because the water depth required for the terminal would place it below the perennial Arctic pack, and laying any pipelines to such a location would hardly be practical.

This concept was studied by an industry team consisting of Newport News Shipbuilding, Westinghouse Oceanic Division, Bechtel, Inc., and by Mobile Shipping and Transportation Company, for the U.S. Maritime Administration. No further work on this concept has been done since the study was completed.

2. Ice-Cutting Tanker ("SLED")

Sea Log Company proposed the ice-cutting tanker concept shown in Figure 3-19. The tanker would cruise below the ice with a pylon containing a rotary cutter and command bridge protruding above the ice. The assumed cargo capacity (300,000 DWT) was over 2-million barrels.

Cost analysis comparing SLED with an ice-breaking tanker and a semi-submersible ice-breaking tanker (described in the next section) indicated that for oil transported from Prudhoe Bay, SLED cost in dollars per barrel was the lowest (8.0, 3.5 and 3.0, respectively).

The development status of this concept is similar to that of the ice-cutter described before. No further work has been done on it since Sea Log Company completed their studies a few years ago.

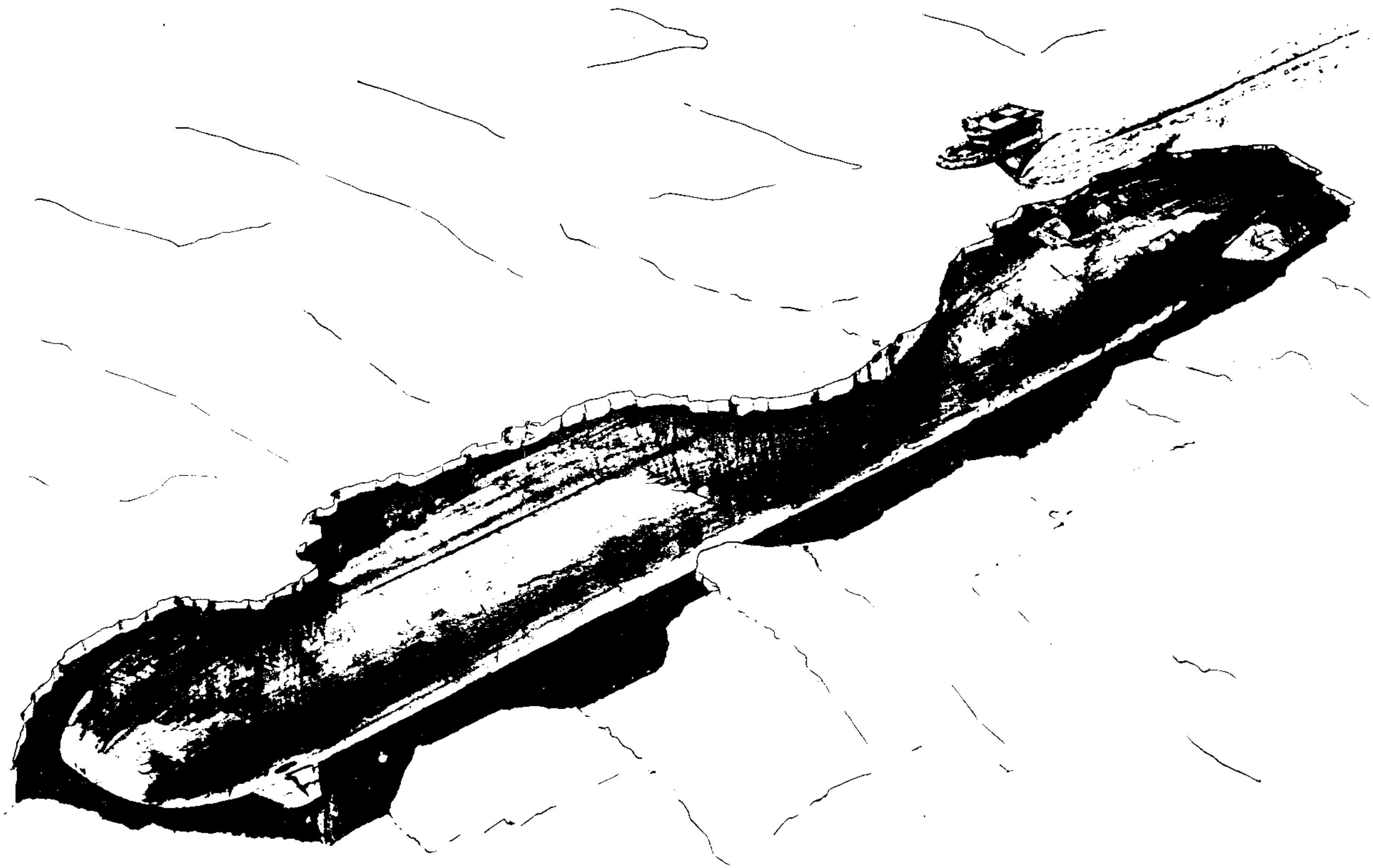


Figure 3-19. 300,000 DWT "Sled" Tanker in Ice (Sea-Log Publication)

3. Semi-Submersible Ice-Breaking Tanker (SSIT)

The concept of a SSIT was proposed by Sandnaes (1975) from Aker Group, Norway. Sandnaes studied different ice-breaking tankers as shown in Figure 3-20, finally selecting the SSIT (bottom picture in Figure 3-20) because only slender fore or aft structures were exposed to ice resistance and the ice-cutting edges at the bow and stern offered greater flexibility to the SSIT for ice-breaking. The SSIT had a 250,000 DWT cargo capacity (under 2-million barrels) and required 60,000 tons of water ballast for stability. The propulsion unit of 125,000 SHP with steam or gas turbines permitted cruising at 15 knots and had an ice-breaking capability of 3.5m (11 ft) of ice at 4 knots. When thicker ice was encountered, the SSIT could either ram the ice or break it by discharging some of its ballast under the ice, thus generating 40,000 tons of uplifting force for ice fracture. The estimated cost of the SSIT was $125 million compared to $51 million for conventional tankers.

The cost, in dollars per barrel of oil transported for conventional tanker, ice-breaking tanker and SSIT, indicated that the last was lowest.

Extensive studies of the SSIT concept were done by the Aker Group in Norway during the 1970/71 period. It is not known whether any further work has continued since that time.

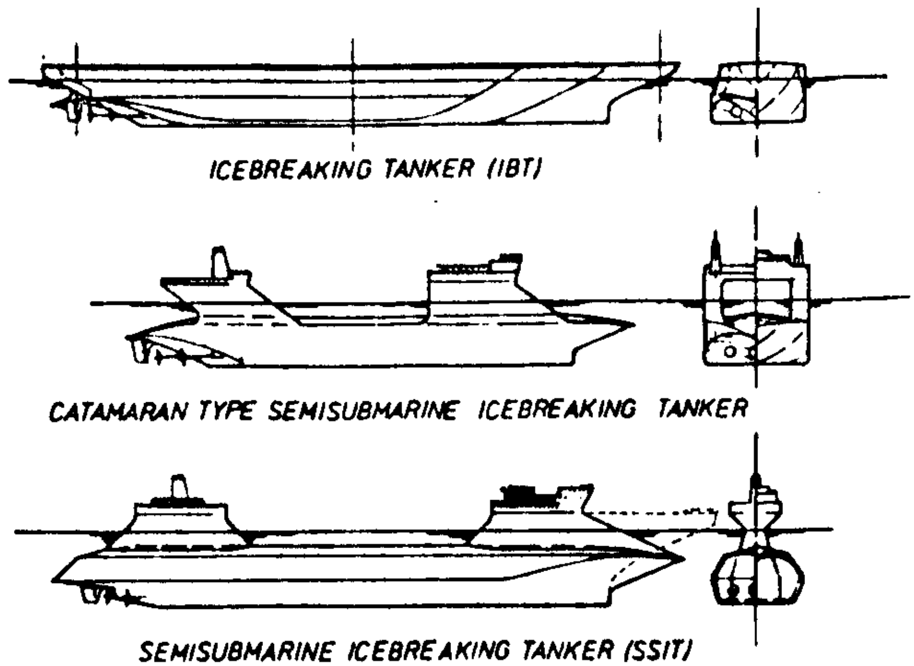


Figure 3-20. Principal Concepts of Arctic Tankers (Sandnaes, 1975)

4. The Arctic Marine Locomotive

Dome Petroleum, Ltd., proposed the Arctic Marine Locomotive (AML) shown in Figure 3-21. The AML would be built as a Class 10 ice-breaker and would, therefore, be the most powerful in the world (the Russians have two Class 7 nuclear ice-breakers).

The proposed AML, powered by 150,000 SHP turbines, displaced 45,000 tons and could move at 3 knots through 3m (10 ft) thick ice with 10/10 ice coverage. It could handle all first-year ice ridges in the Arctic and multi-year ridges up to 10m (30 ft) when encountered in 1.5m (5 ft) first-year ice with 10/10 coverage. The design of the AML incorporated a unique feature in the concave design of the sterm for close-coupled pulling of ships or barges. The AML could also operate as a pusher tug to allow Arctic Class oil carriers or LNG carriers to move through heavy ice. The cost of an AML with a three-year pilot operation is estimated at $165 million (Dome private report, 1977).

Dome Petroleum performed extensive design and economic analysis of this concept two years ago. No further work on it has been done since.

The most likely candidates for Beaufort field development and production from the concepts discussed before, are ranked in descending order. The order is based upon their feasibility, economic viability and applicability for shallow water operation.

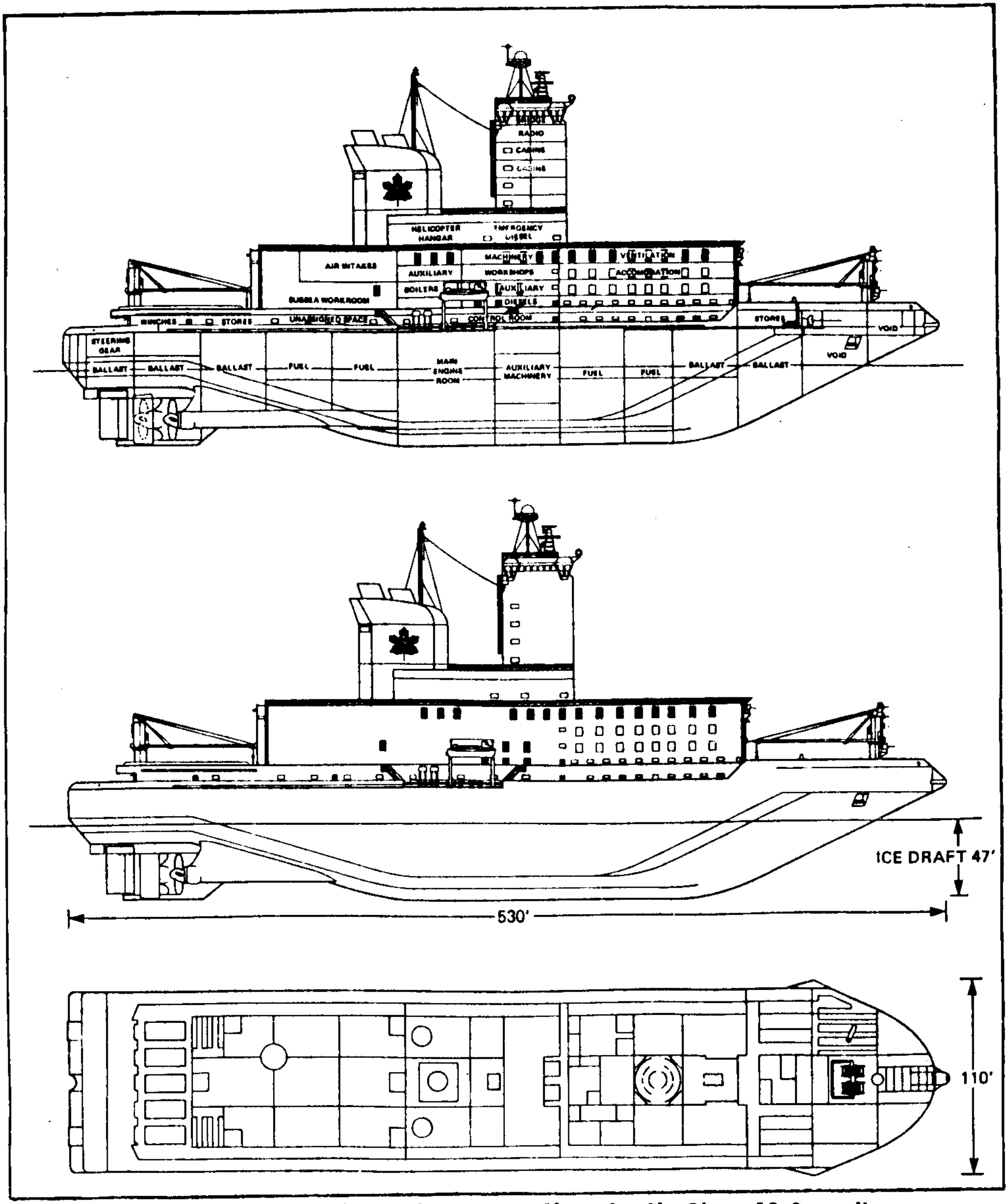


Figure 3-21. Arctic Marine Locomotive, Arctic Class 10 Capacity (Dome Petroleum, Ltd., Publication)

Barrier Islands
Artificial Islands
Grounded Barges
Monopods and/or Cones

D. SUPPORTING ELEMENT

1. Subsea Completion

Subsea, bottom-founded valve systems either in the form of blowout preventers (BOP) for exploratory development or Christmas trees for production wells came into use more than 30 years ago (Sellars, Wickizer, 1977). Today, approximately 100 underwater well completions are producing and more than 200 (Chateau, 1977) systems have been tested. The incentive for diverless-installed subsea systems lies with the possibility of operation at great water depth (>2000 ft) or in a rough climate with moderate water depths. The ice ridge zone in the Beaufort Sea offers another possibility for production subsea systems, since it may not be feasible to place a permanent structure there. Another possible application for subsea completion systems is for periphery wells outside the range of directional drilling connected with gathering lines to a fixed platform.

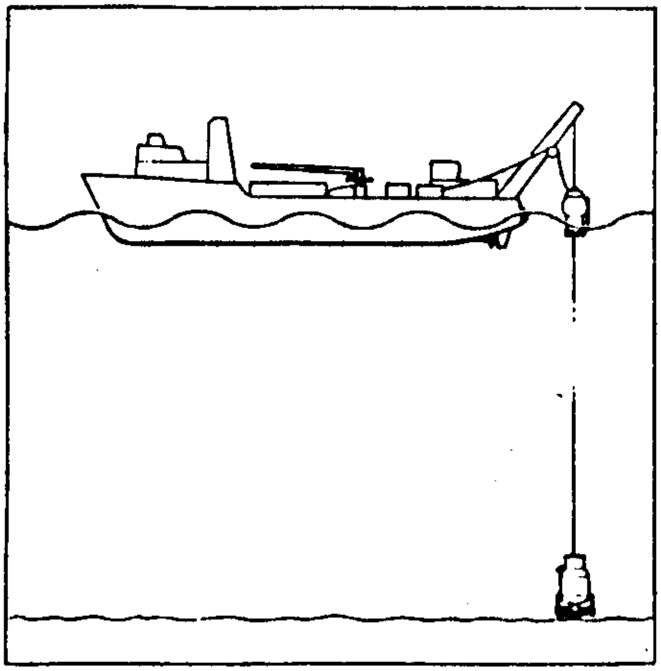
The subsea wellhead system consists of surface equipment controlling the operation, an interconnecting link, and subsea equipment. The surface control equipment could be placed on a fixed or a mobile platform, the interconnecting link could be all hydraulic or electro-hydraulic with a multi-wire or a multiplex communication system (Stivers, 1976).

The subsea equipment could be a dry -1 atm system such as developed by Lockheed and shown in Figure 3-22. This system, which was tested in 110m (360 ft) of water in the Gulf of Mexico (Mason, 1976), consists of a wellhead cellar which is attached in a watertight manner to the wellhead and permits shirt-sleeve operation. There is a service capsule for transferring the personnel from the surface to the wellhead cellar; and ocean floor manifolding for a multi-well operation.

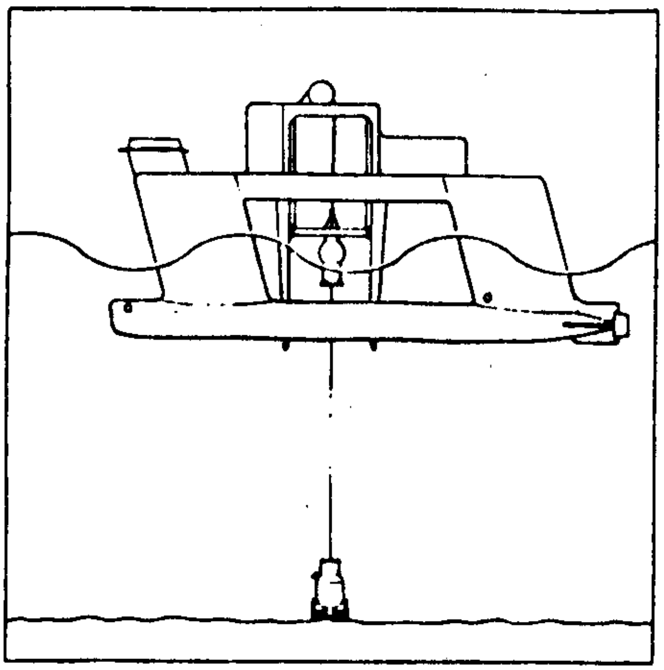
The alternative of a subsea system is a wet system such as the SPS (Subsea Production System) tested by Exxon off the Louisiana coast in 52m (170 ft) of water (Burkhardt, 1977). This system can be remotely installed, maintained, and disassembled and may be more suited than a dry system for Arctic offshore operation.

The technology of wet systems is well established and components are manufactured by companies such as Cameron Iron Works, Reagan Offshore International, and Vetco, with control systems developed by such organizations as TRW-Subsea Petroleum Systems. Subsea production processing plants were built by the National Tank Company for offshore pilot operations.

Figure 3-23 shows a subsea BOP and production Christmas tree manufactured by Reagan International for Panarctic Oil for exploratory and production gas drilling in offshore



TWIN-PONTOON SEMI-SUBMERSIBLE MIGHT BE ARCTIC SUPPORT VESSEL.



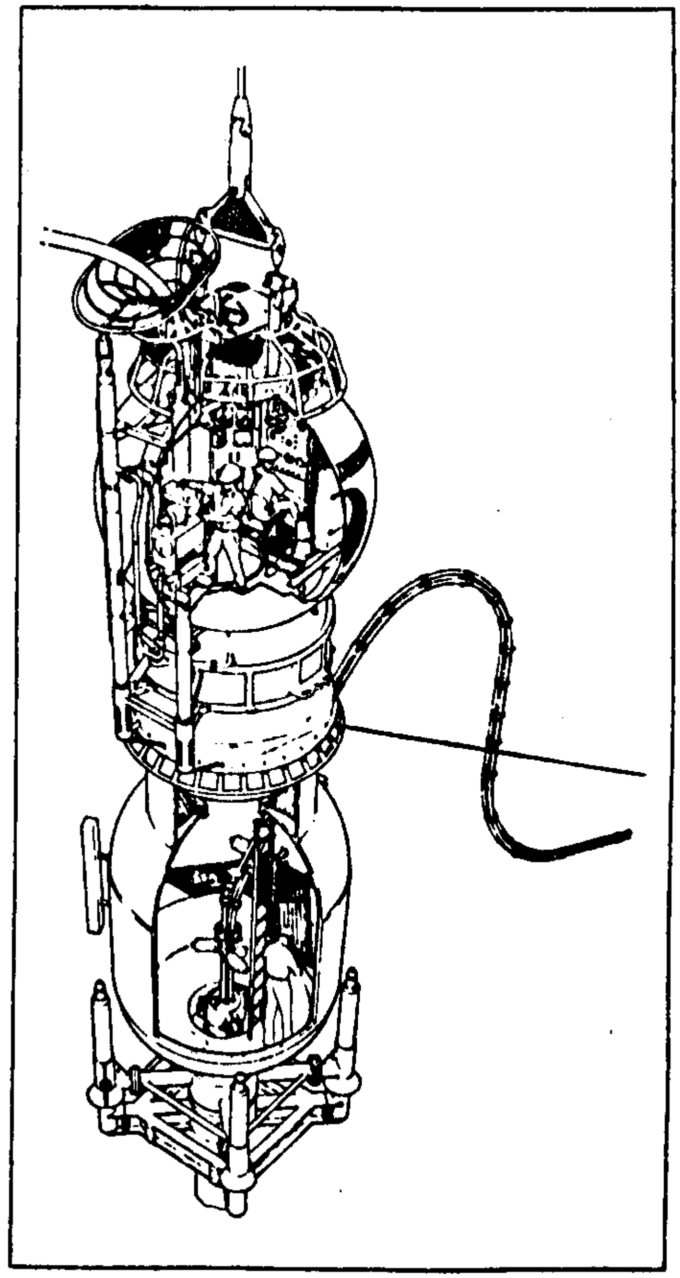
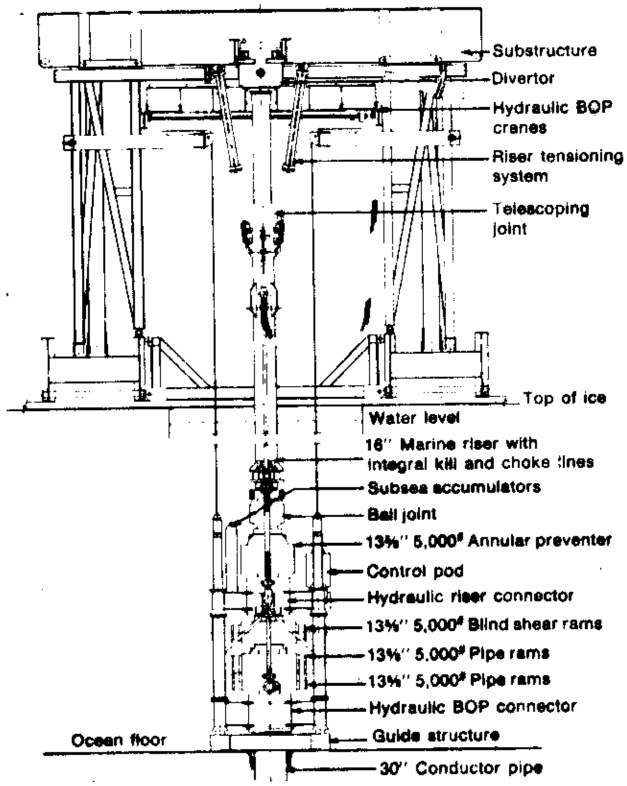


Figure 3-22. (Mason, 1976)

DRY SUBSEA COMPLETION SYSTEM



THE 13-INCH, 5,000 PSI BOP STACK CAN BE HANDLED IN ONE PIECE DURING ALL DRILLING OPERATIONS, OR IT CAN BE DISASSEMBLED INTO TWO PIECES FOR AIR TRANSPORT

THE DIVERLESS SUBSEA CHRISTMAS TREE WILL PRODUCE INTO TWO 6-INCH FLOW LINES. PROVISIONS HAVE BEEN MADE IN THE TREE TO ALLOW GLYCOL INJECTION

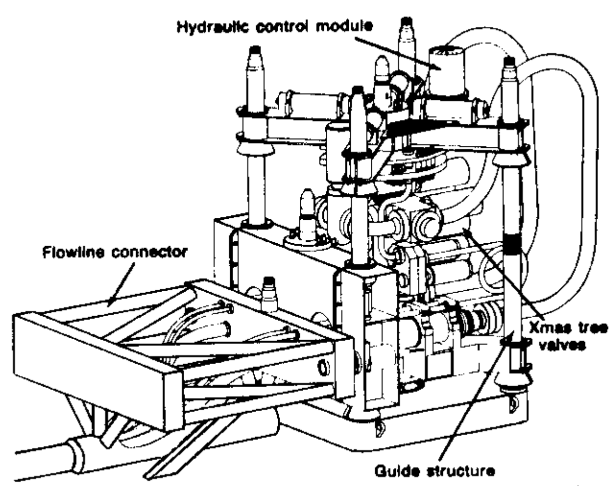


Figure 3-23. BOP Stack and Christmas Tree, Regan Offshore (World Oil, 1977)

Canadian Arctic Islands. The tree was connected with a pipeline to nearby onshore processing facilities.

To avoid the hazard of ice scouring, which is common in the Beaufort and Chukchi Sea to depths of approximately 60m (200 ft), the BOP or Christmas tree has to be placed below the mudline either in caissons or in a "glory hole" at a depth dictated by the size of the scours observed. Figure 3-24 shows a Vetco design of a Christmas tree packaged in a caisson. In Arctic offshore applications, the top of the protective cover shown in this figure would be placed below the scour depth and the flow-lines would also be buried.

There is a substantial amount of experience on subsea oil and gas BOP's, or Christmas trees. However, this is mostly limited to milder climates and the only subsea valving in Arctic Seas was used in exploratory gas drilling by Panarctic Oil and Dome Petroleum. Panarctic has one subsea tree on a gas producing well in the vicinity of the Canadian Arctic Island.

Before their wide application, subsea components for oil wells in the Beaufort Sea will require high reliability, diver-less maintenance and will have to be proven under actual operating conditions. A lack of year-round access may limit the applicability of subsea systems in Arctic pack ice areas.

The cost of a subsea BOP, or tree, such as used in the gas well by Panarctic Oils, is about $1 million.

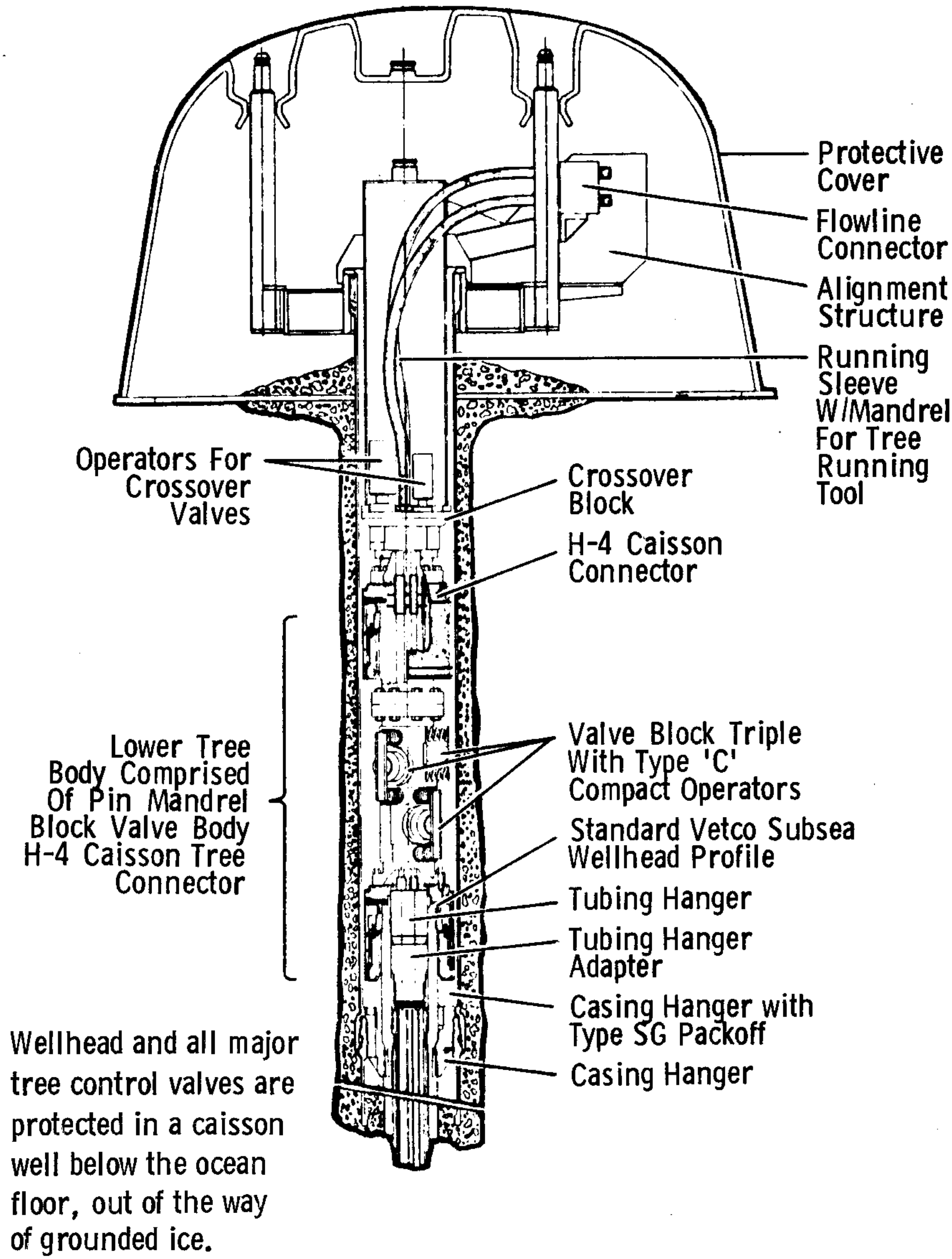


Figure 3-24. Wellhead (Vetco)

IV. DESIGN REQUIREMENTS IMPOSED BY THE ARCTIC OCS ENVIRONMENT

Section I.F of this report provided a general discussion of environmental hazards associated with the Arctic offshore environment. This section examines the engineering aspects of these hazards and their effects on offshore structures. Only the more serious design related hazards such as ice, waves, storm surge, permafrost, and seismicity are considered. As pointed out previously, however, there is a wide range of lesser problems such as low temperature, restricted visibility, and inadequate weather forecasting which must be taken into account in the overall development strategy.

A. ICE

There is a wide spectrum of engineering problems related to ice. Most of these are associated with the movement of ice and the resulting forces, and other phenomena generated by it. A secondary, and less serious hazard, is superstructure icing which is the accumulation of ice on structures and machinery exposed to the atmosphere.

1. Ice Movement

Ice movement and its consequent impingement upon structures transmits forces which need to be resisted by the structure and its foundation. These forces, as they act on a sand/gravel island were discussed in Section II. Ice movement is also the cause of ice pileup on slopes and beaches and of scouring or gouging of the seafloor.

Ice movement can be produced by thermal expansion and contraction, by currents, and by winds or waves. Winds acting alone are capable of exerting huge forces on sheets of ice. More often, however, it is the combination of wind and currents which produce pack ice motion and exerts forces on the landfast ice causing it to move.

Ice movement observations have been made over a period of years using a variety of different techniques. Those which have been employed include taut wire method, visual survey triangulation, strain gauging (Cooper, 1975), lasers, radar (Weeks, 1977), aerial photography (Hanson, 1978), and satellite (Sobczak, 1975 and Dehn, 1974). The results of these various observations are summarized below.

The magnitude of movement varies as a function of season, location, and condition of the ice. The season, with respect to ice movement, can be divided into two periods: (1) the winter season when the ice is thicker than 1m (3 ft); and (2) freeze-up (fall) and breakup (spring) which are characterized by either thin or weakened ice.

Location can be divided broadly into three zones. Zone 1 includes the landfast ice between the mainland and barrier islands; Zone 2 extends from the barrier islands to the shear or grounded ridge zone; and Zone 3 is the ridge zone. Zone 1 averages a few kilometers (miles) in width. Zone 2 varies from 15 to 30 km (10 to 20 mi) except at locations such as Harrison Bay, where there are no barrier islands and the zone may extend to 80 km (50 mi) (Shapiro and Barry, 1978). Zone 3 may extend for tens of kilometers (tens of miles). Considerable annual variation may be found in Zones 2 and 3 as a result of climatic differences from year to year.

Ice movements are usually of short duration. Fifteen to thirty minutes appears to be a typical length of such an event (Kovacs and Sodhi, 1978). The potential energy accumulated in the ice from wind and current, is rapidly released once a break in the ice formation is initiated at some location.

Ice movement observations over a period of years were made by standard surveying triangulation methods, by strain gauging (Cooper, 1975), by lasers, by radar stations with transponders located on ice in different locations (Weeks, 1977), by aerial photography (Hanson, 1978), and by satellites (Sobczak, 1975 and Dehn, 1974).

The magnitude of movements can be summarized in terms of seasons and zones defined above. During freeze-up or breakup ice motion is predictably large. In Zone 1 it can be measured in tens of meters (up to $\sim$100 ft); in Zone 2 hundreds of meters (up to $\sim$1000 ft); and in Zone 3 it may be several kilometers (miles) (Weeks, 1978). During the winter, after the landfast ice sheet has thickened, ice movements in Zones 1 and 2 are considerably smaller. In Zone 1 they may range up to a few meters (∿10 ft) and in Zone 2, up to a few tens of meters (∿100 ft) (Shapiro, 1978 and Barry et al, 1977). In Zone 3, however, appreciable motion can still occur, being a function of pack ice dynamics.

In the Chukchi Sea, there is little data regarding ice movement except in the vicinity of Barrow. Several factors suggest that results of Beaufort Sea studies are not applicable to the Chukchi. The Chukchi Sea (except for the lagoons) has relatively few barrier islands to protect and stabilize the landfast ice sheet. Furthermore, the landfast ice zone is much narrower than in the Beaufort and is subject to considerably greater spring and winter pack ice movement (Shapiro and Barry, 1978). Other differences include a smaller interannual fast ice variation along the Chukchi as well as a decrease in the intensity of ridging (Barry et al, 1977).

In spite of those studies which have been done to measure ice movement, the statistical data base required for structural design is still limited. A larger data base consisting of measurements having both geographic and temporal continuity is required to estimate potential extremes. Any structure deployed in the open ice sheet for a period of years will be required to withstand many ice invasions. A more reliable prediction of expected ice forces would result in a safer design.

2. Ice Strength and Ice Forces Acting on Structures

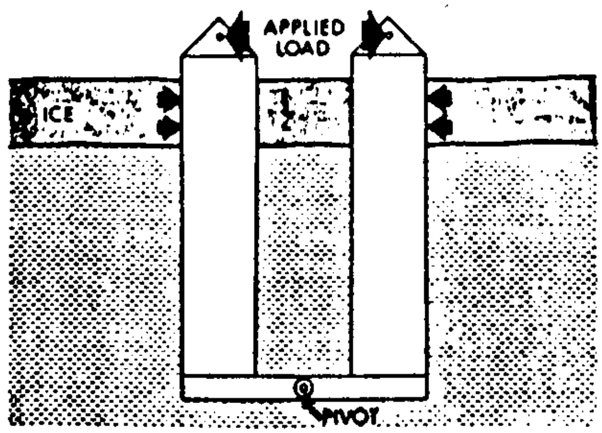
Ice is a nonhomogeneous material and its strength is a function of many variables. Some of the more important factors influencing strength include age, location in an ice sheet, temperature, salinity, gas content, crystal orientation, strain rate, structure, dimension in relation to ice thickness, and mode of failure (Schwarz and Weeks, 1977). As might be expected, the literature reports a wide variation in the strength of ice, particularly the crushing (compression) strength. Small scale laboratory tests of ice crushing strength indicate values up to 120×10^2 kPa (1700 psi) (Schwarz and Weeks, 1977). On the other hand, data based on actual ice pressures measured in some Alberta moves, indicated design pressures of 9×10^2 to 14×10^2 kPa (150 to 200 psi) (Reddy et al, 1975). The American Petroleum Institute publication RP 2A recommends a value of ice compressive strength of between 200 and 500 psi. These discrepancies notwithstanding, an accurate knowledge of the compressive strength of ice will play a major role in the economics of Arctic platform construction. Reddy et al (1975), for example, report that reducing the design strength from 400 psi to 100 psi, reduced the cost of piers in Battle River, Alberta, by 40 percent. Experience in the Cook Inlet, after full scale tests, also allowed some reduction in previously assumed design strengths to 300 psi.

a. Measurement Techniques

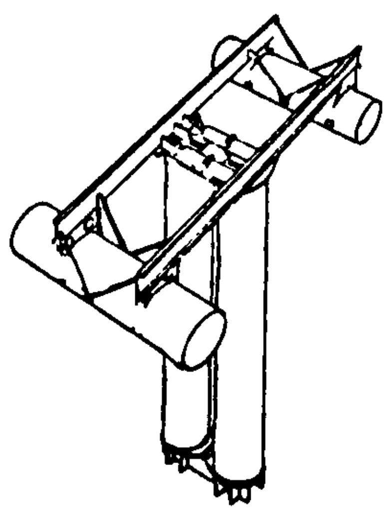
The wide range of values quoted for compressive strength can be attributed partially to different methods used for testing ice strength. Tests have been conducted both in laboratories and *in situ* using a variety of equipment. One of the most common methods of measuring compressive strength utilizes hydraulic rams of various shapes and sizes. The compressive strength is calculated from the fluid pressure required to fail the ice or from stress gauges embedded in the ice.

One of the *in situ* methods employs a device known as the "Nutcracker" (Figure 4-1) developed by Croasdale. It consists of two loading legs, hinged at the bottom, which can be pushed apart by three hydraulic rams linking the legs together at the top. In essence, it works like a nutcracker in reverse. Ice is failed by spreading the legs rather than by closing them. Floats attached to two outrigger beams (see bottom, Figure 4-1) enable the device to be floated to the area of interest prior to freeze-up. After the "Nutcracker" is frozen-in, the floats are removed, and the tests conducted. Loading legs of .75 m (2.5 ft) diameter and 1.5m (5.0 ft) have been used for testing the device (Croasdale, 1974).

The "Nutcracker" is used to fail ice through the entire length of its bearing legs. It does not provide any information regarding vertical variations in strength which may exist through an ice sheet. Another device, consisting of a



OPERATING PRINCIPLE



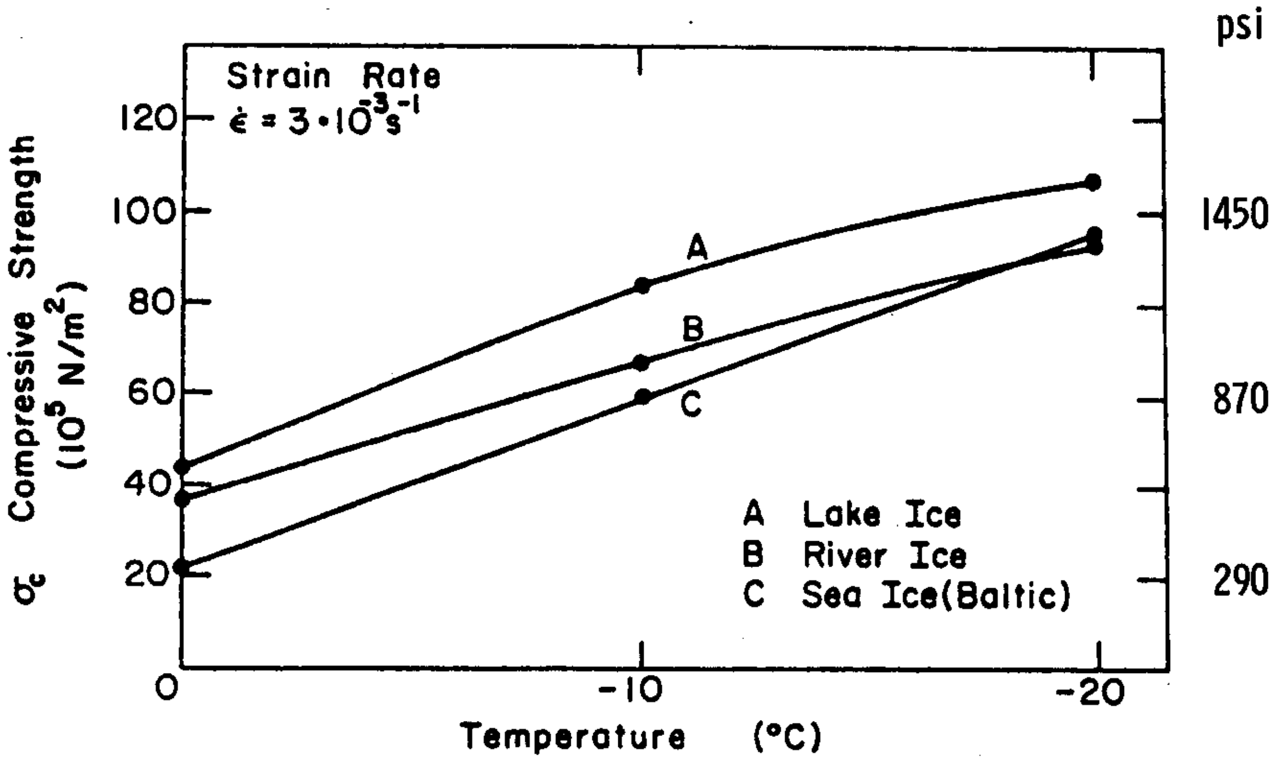
PICTORIAL VIEW

Figure 4-1. Nutcracker Ice Strength Tester (Croasdale, 1974) horizontal jack which can be lowered through a small borehole (0.15m or 0.5 ft) has been used successfully to measure relative strength at discrete depths within an ice sheet (Kivisild, 1975).

b. Compressive Strength and Crushing Pressure

Ice compression strength versus temperature is shown in Figure 4-2. It illustrates the inverse relationship between strength and temperature. The series of curves show decreasing strength with increased salinity (for instance, compare "A" with "C"). The relatively high overall strengths measured are an indication that small dimension samples were used in testing. The interrelationship of such ice properties as temperature, gas content, salinity, and strength throughout the ice depth, appears to influence failure modes directly. This is particularly true in terms of non-uniformity and progressive deformations.

Another variable which has important engineering implications is the ratio of ice thickness to pile diameter. This relationship is illustrated in Figure 4-3 and also in the variation of the C_f coefficient in the top graph in Figure 4-9. Both show a marked decrease in ice crushing pressure as pile diameter is increased. The curves clearly suggest that structures which utilize large diameter members can fail ice at lower average stress than structures which utilize slender members.



COMPRESSIVE STRENGTH OF ICE AS A FUNCTION OF TEMPERATURE LOAD APPLIED PERPENDICULAR TO THE GROWTH DIRECTION.

Figure 4-2. Compressive Strength of Ice (Schwarz, 1970; Schwarz & Weeks, 1977)

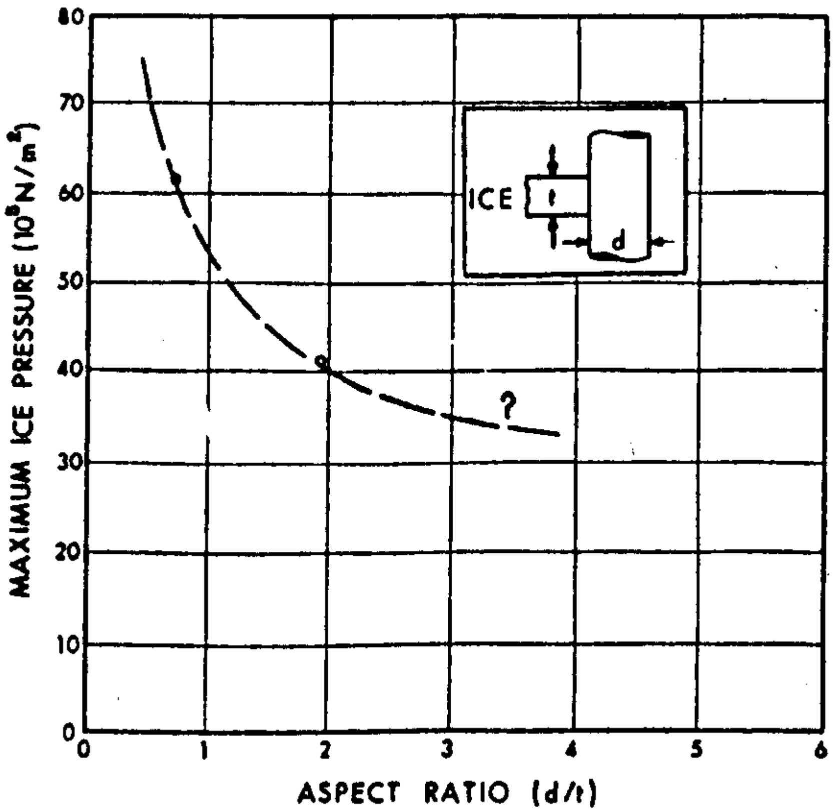


Figure 4-3. Crushing Pressure of Arctic Ice Vs. Aspect Ratio (Croasdale, 1974)

Other structural variables which may have a marked effect on ice strength are illustrated by the equation at the top of Figure 4-4. σ_{ref} is a function of the ice condition and comprises such variables as temperature, salinity, gas content, etc. The other factors, I, m, and k, are variables which, to an extent, can be externally controlled. In general, the equation shows that crushing pressure can vary widely depending upon the size, shape, and degree of surface contact with a structural member.

c. Flexure Strength

Flexural strength of ice appears to be less variable than compression strength. Figure 4-5 shows the relationship between brine volume and flexural strength. Data include laboratory tests and field tests of both Beaufort Sea and Antarctic ice. A similar inverse relationship exists between strength and salinity as that found for compression strength. The graph at the bottom of Figure 4-5 shows that flexural strength is greater than uniaxial tensile strength by approximately 150 kPa (22 psi).

d. Shear Strength

Shear strength of ice as a function of brine volume is shown in Figure 4-6 (Schwarz and Weeks, 1977). Voitkovskii (1960), however, reported lower values than those in Figure 4-6 and observed that shear strength is approximately one-half of the tensile strength.

Figure 4-4. Ice Strength

- CRUSHING (COMPRESSION): $\sigma = I \cdot m \cdot k \cdot \sigma_{ref}$ (Croasdale)

  σ_{ref} - REFERENCE STRENGTH IN COMPRESSION

  I - INDENTATION FACTOR [1.0 FOR WIDE STRUCTURES, 2.5 FOR SLENDER (d/t = 1.0)]

  m - SHAPE FACTOR (~ 1.0 FOR CIRCULAR SHAPES)

  k - CONTACT COEFFICIENT (1.0 FOR PERFECT CONTACT)

- FLEXURAL STRENGTH: $\sigma = 960 - 1920\sqrt{\nu}$ IN kPa (Vaudrey)

  ν - BRINE VOLUME, FRACTION

- MODULES OF ELASTICITY: $E = 5.32\,(10^6) - 1.3\,(10^7)\sqrt{\nu}$ IN kPa (Vaudrey)

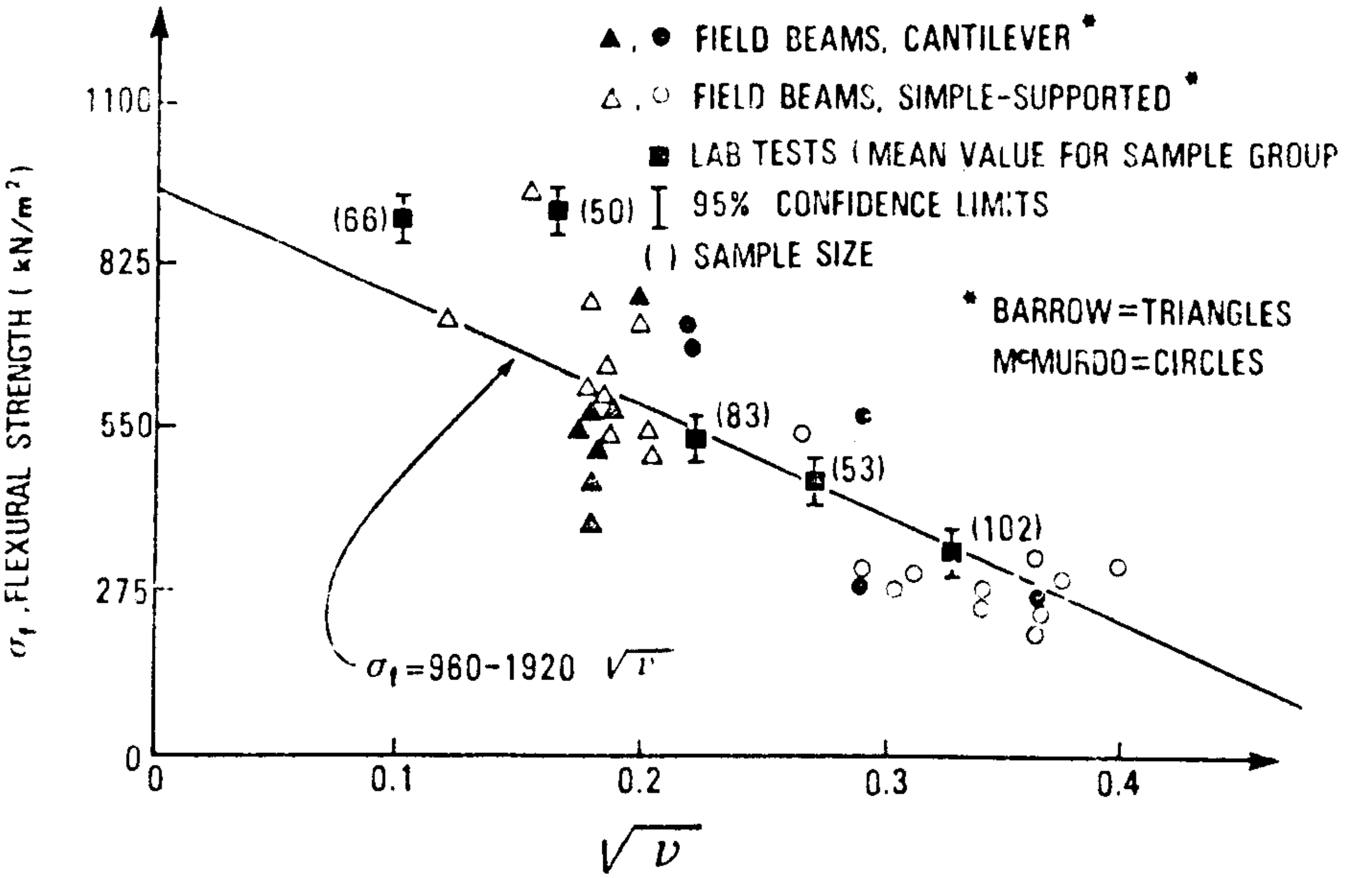
- TYPICAL VALUES: [FOR BRINE VOLUME ν = 0.026 (4.7 $^0/_{oo}$)] Temp. -10^0C

  CRUSHING 500 - 600 psi d ~ 5 ft (Croasdale)

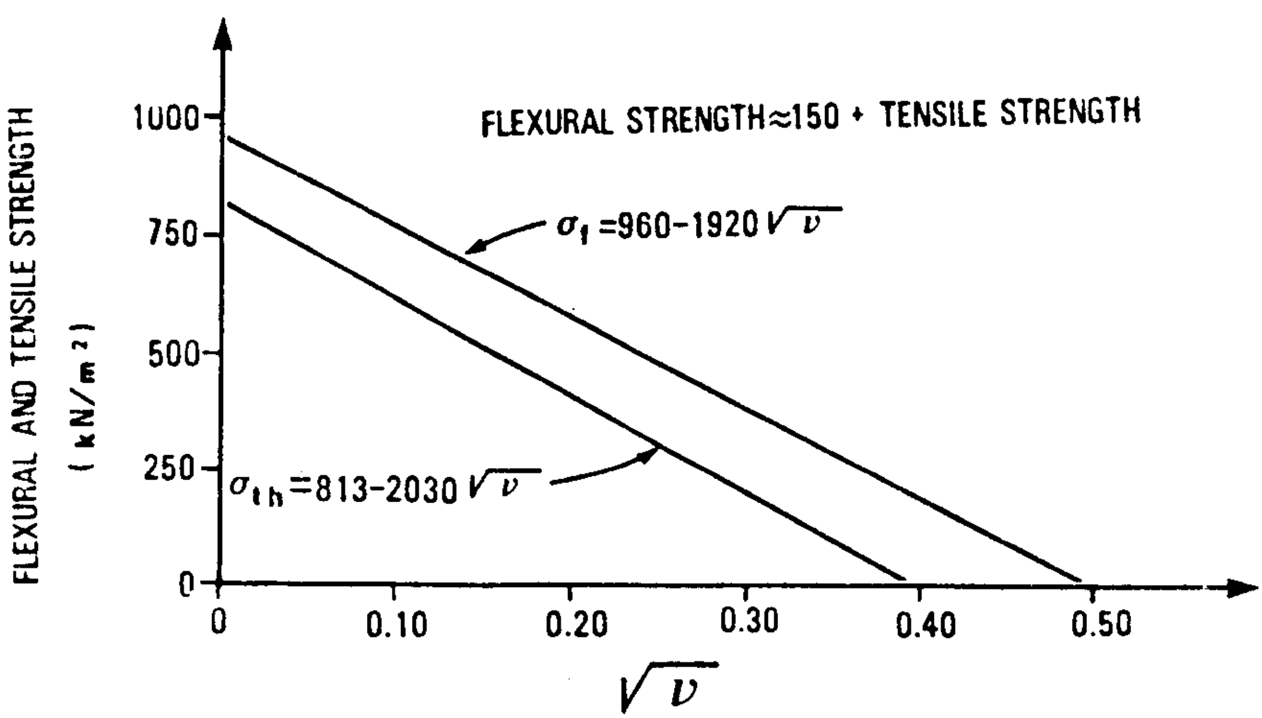
  FLEXURAL 85 - 145 psi (Tinawi & Murat)

  SHEAR ~ 75 psi

  MODULUS 0.6×10^6 psi (Tinawi & Murat)

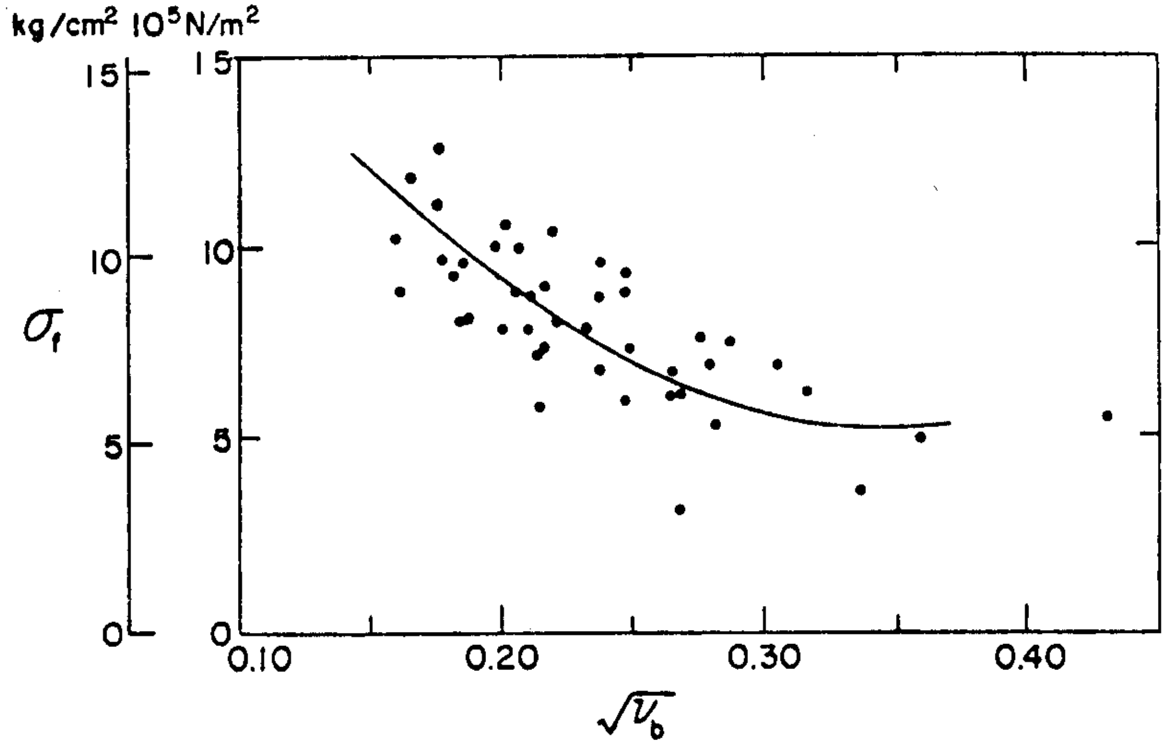


Flexural Strength Versus the Square Root of Brine Volume



Comparison of Flexural and Horizontal Tensile Strength Versus the Square Root of Brine Volume

Figure 4-5. Strength Versus the Square Root of Brine Volume (Vaudrey, 1977)



SHEER STRENGTH AS A FUNCTION OF THE SQUARE ROOT OF BRINE VOLUME

Figure 4-6. Sheer Strength (Schwarz & Weeks, 1977)

Typical values for crushing, flexural, and shear strengths as well as modulus, are found at the bottom of Figure 4-4. The values quoted are for the temperature and salinity stated.

e. Ice Forces

Ice forces impose both static and dynamic stresses on a structure. Static loads on a circular pile are expressed by the upper two equations in Figure 4-7. The equation by Tryde (1975) indicates nearly linear relationship between ice force and pile diameter and it also illustrates the ratio relationship of diameter (d) to ice thickness (h) (k coefficient) discussed previously. If, for example, $d/h = 6$, then $k = 3.1$. If $d/h = 0.1$, then $k = 5.2$. The latter value represents a limiting condition for this equation.

The second equation (Figure 4-7) by Saeki (1977) indicates that ice force is proportional to the square root of pile diameter. Although Saeki (1977) plotted his test results (Figure 4-8), he gives no values for ice compression strength (σ_c). If the σ_c that Saeki used was large enough, the product of $\sqrt{d}\cdot\sigma_c$ may be close to $d\cdot\sigma_c$ providing smaller values of σ_c are used. These two equations are another example of uncertainty in ice strength values.

The forces acting on a conical structure, such as monocone, can be estimated by the lower equation in Figure 4-7. This equation, reported by Croasdale (1977), was derived from a model test on a 45° cone in which the ice/steel friction

Figure 4-7. Ice Forces

FORCE ON A PILE:

$F = K \times \sigma_{\infty} \times h \times d$ (TRYDE)

$K - 1 + 2.1 \times \left(0.4 + \frac{d}{h}\right)^{-1}$

σ_{∞} - ICE STRENGTH FOR $d \infty$

h - ICE THICKNESS

d - PILE DIAMETER

OR

$F = 5 \times \sqrt{d} \times h \times \sigma$ (SAEKI)

σ - ICE STRENGTH (COMPRESSION) IN Kg/cm^2

h - ICE THICKNESS IN cm

d - PILE DIAMETER IN cm

FORCE ON A CONE:

$F = 1 \times 6 \times \sigma_{\nu} \times h^2 + 6 \times \rho \times g \times d \times h^2$ (CROASDALE)

σ_{ν} - ICE FLEXURAL STRENGTH Kg/cm^2

h - ICE THICKNESS IN cm

d - CONE DIAMETERS IN cm

ρ - ICE SPEC. GRAVITY $Kgsec^2/cm^4$

g - GRAVITY ACCELERATION CM/sec^2

FIRST TERM IS FORCE TO FAIL ICE IN FLEXURE

SECOND TERM IS FORCE TO PUSH THE ICE ASIDE

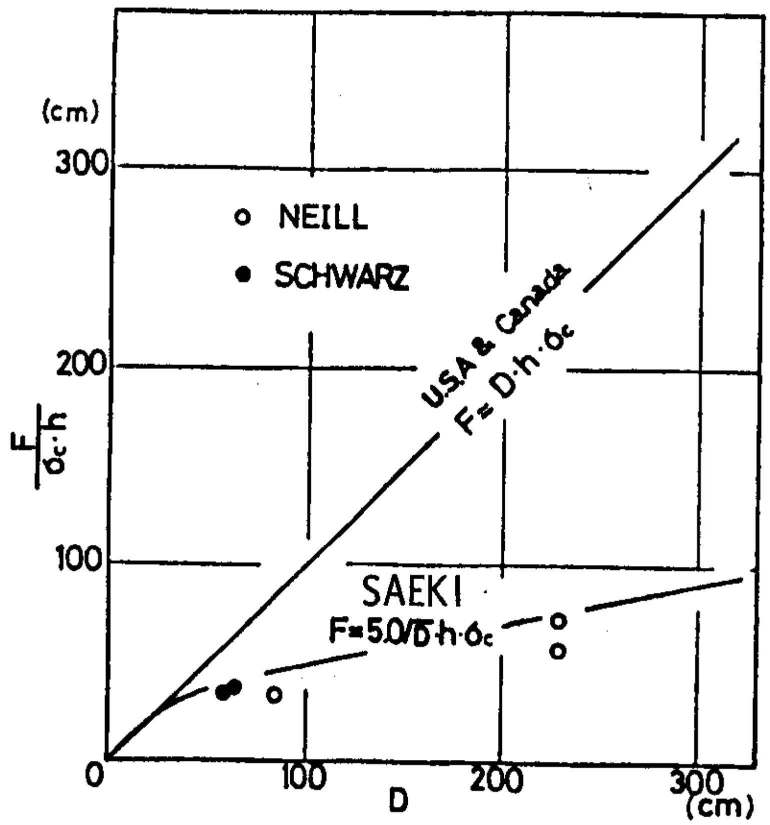


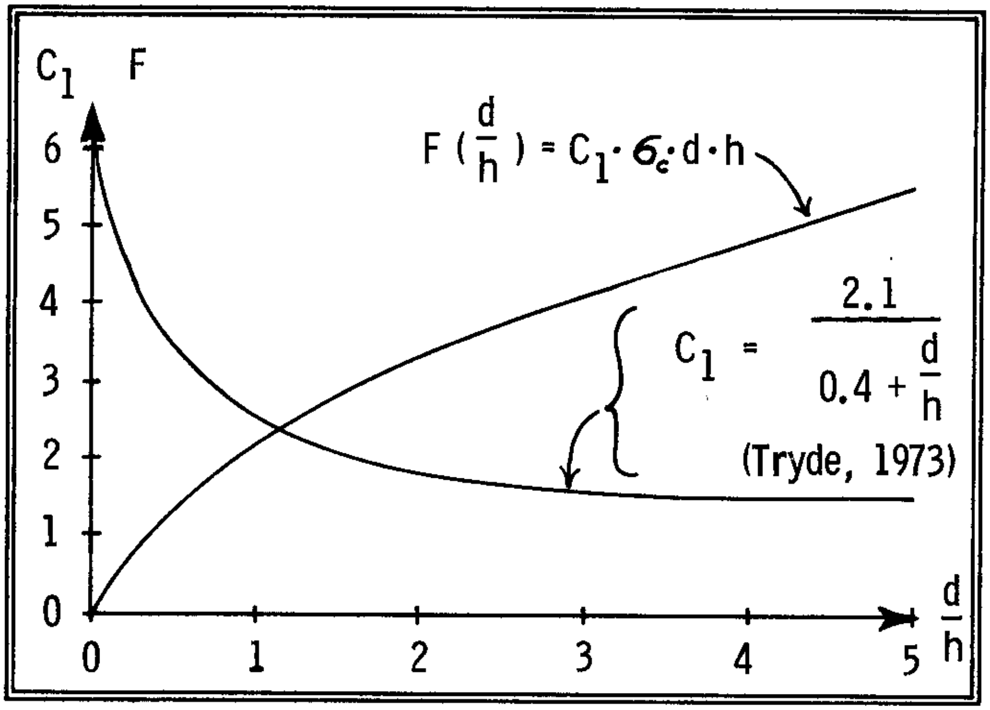
Figure 4-8. Comparison of the Saeki Formula with Formulas Used in USA and Canada (Saeki, 1977)

coefficient was 0.1. The first term represents the force necessary to fail the ice in bending, and the second term that required to push the broken ice up and around the cone. In one example calculated by Croasdale for a 25m (82 ft) diameter cone, the two force components were about equal. Croasdale's calculations also stressed the importance of preventing ice adfreeze on a structure. With adfreeze the force required to break the ice was several times greater than for non-adfreeze conditions.

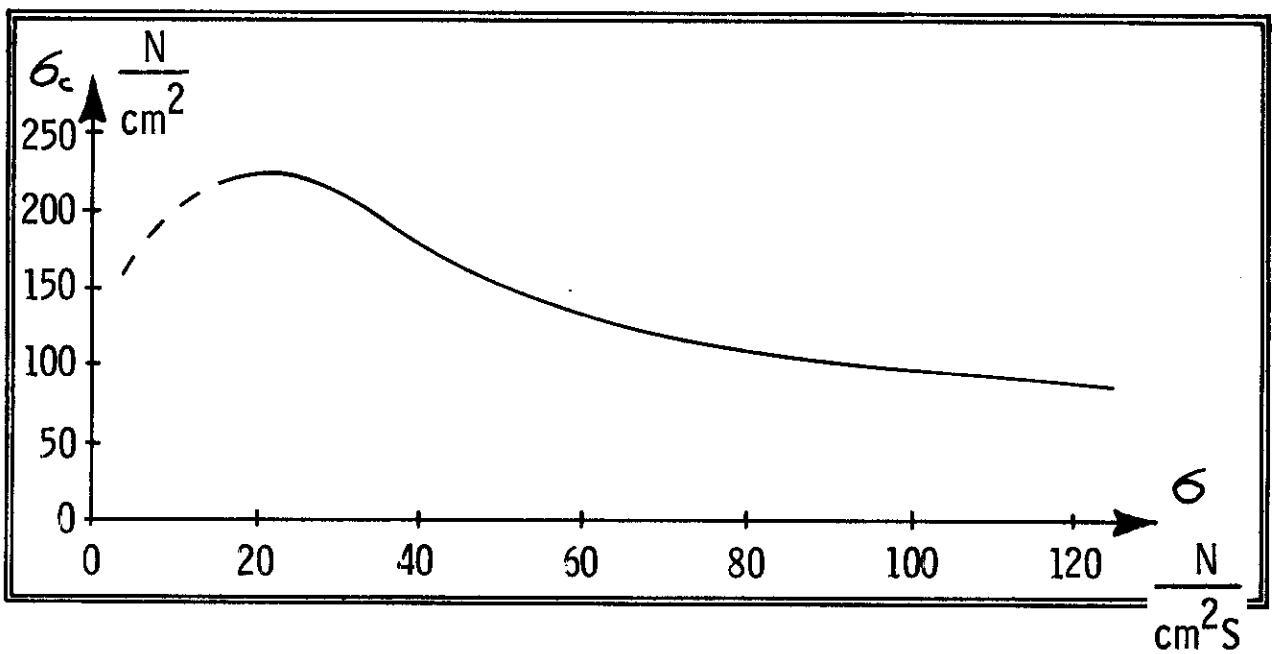
The dynamic stresses which can be produced by ice forces on a structure may be caused by two phenomena. The first is the fact that ice strength varies as a function of the stress (or strain) rate. This is illustrated in the lower graph of Figure 4-9. The second is the force response (deflection) characteristic of a structure. Structures which do not deflect under loading would not be subject to dynamic stresses.

One explanation of dynamic stresses which result from ice loading is found in Määtänen (1977), a portion of which is excerpted below:

> At the very beginning of a loading cycle the deflection of structure is increasing with the velocity of the ice and the resistance of the structure is increasing almost linearly with time. This will continue linearly until the ice crushing strength is exceeded or unlinearly while deflection rate decreases in relation to the ice velocity causing an increase in strain rate. Then according to the figure (4-9) the ice crushing strength is also increasing



ICE FORCE VERSUS DIAMETER TO ICE THICKNESS RATIO
(Määtänen, 1977)



CRUSHING STRENGTH VERSUS STRESS RATE
(Peyton, 1966)

Figure 4-9

making even greater ice loads possible and increasing more the strain rate. The process continues until the maximum point in the ice strength curve, Figure 4-9, is achieved after which the crushing will start. The process follows the above scheme also in the linear case, the transition to crushing is then so sudden that unlinearities remain insignificant.

At the point of maximum ice strength the resistance of the structure exceeds the resistance of the ice and the spring-back of the deflection starts. This increases the strain rate still more causing now a decrease in the ice crushing strength. The deflection spring-back may then continue more easily and faster accelerating thus itself. The deceleration starts when the deflection has become so small that the ice load exceeds the resistance force of the structure even with a great strain rate. The crushing then stops and the next loading cycle may start.

If the descending portion of the crushing cycle is considered as a negative damping effect, no vibration will occur when the internal positive damping of the structure exceeds the negative damping of ice. Amplified vibrations will occur, at some limit cycle, if the net negative ice damping during vibration exceeds the internal positive damping of a structure. The internal damping coefficient of steel structures, including hydrodynamic damping, is between 0.02 and 0.05. This is lower than the negative damping by ice. Consequently, vibration may occur. This factor should be considered in the design of relatively slender structures such as monocones and monopods. A lighthouse in Finland, the Kemi I, is believed to have failed because of ice-induced vibration (Määtänen, 1977).

It should be pointed out that the Määtänen explanation of vibrations, based on ice strength vs strain rate dependence, is only one of the theories proposed. Payton (1968), for instance, considered ice-induced vibrations as being independent of structural stiffness.

Many of the ice force measurements which have been made rely on scaled-down models in laboratory tests. It is appropriate, therefore, to discuss the limitations of extrapolating these data to full scale. Many scaling problems exist because it is impossible to simulate inertia, viscous, and gravity forces simultaneously. This difficulty arises since the Reynolds Number represents the ratio of inertia to viscous forces and Froude's Number the ratio of inertia to gravity forces. Atkins (1975) has shown that to maintain these two ratios constant for a model and full-scale prototype a tank fluid would be required for which:

$$\frac{\nu_p}{\nu_m} = \lambda^{2/3}$$

where ν is the kinematic viscosity for prototype (p) and model (m), and λ is the scale factor. Since this is not feasible, it is customary to scale according to Froude's Number and to correct the results by other data showing the effect of Reynolds Number.

Atkins (1975) also arrived at a conclusion regarding the ice-cracking mechanism. He stated that, in addition to maintaining Froude's Number equality, the model ice strength should be scaled down linearly. Thus:

$$\sigma_m = \frac{1}{\lambda} \cdot \sigma_p$$

where σ_m is the model ice strength, σ_p is the prototype ice strength, and λ is the scale factor. This is now well known and it points out the need to exercise caution in extrapolating model tests and to be sure that appropriate corrections are applied to compensate for imperfect simulations.

3. Ice Override

Ice override is a problem which needs to be considered in the design of low freeboard structures, particularly artificial islands in shallow water. Kovacs and Sodhi (1978), who have reviewed observations on this phenomenon made since 1835, noted that ice override, and the consequent rubble piles which are formed, may extend to 50m (165 ft) inland. Furthermore, the ice has been observed to mount steep cliffs as high as 9m (30 ft).

Figure 4-10 illustrates the mechanism of ice override as observed by Kovacs (1978). It is interesting to note that in shallow water the ice will bottom, and then the ice above will grow at a more rapid rate.

The forces generated in the pack ice-landfast ice boundary correspond to maximum stresses of 207 kPa (30 psi). Those measurements were monitored by Nelson outside the barrier islands of Prudhoe Bay. Warmer ice can transfer greater forces to structures because of its greater ductility (Shapiro, 1977).

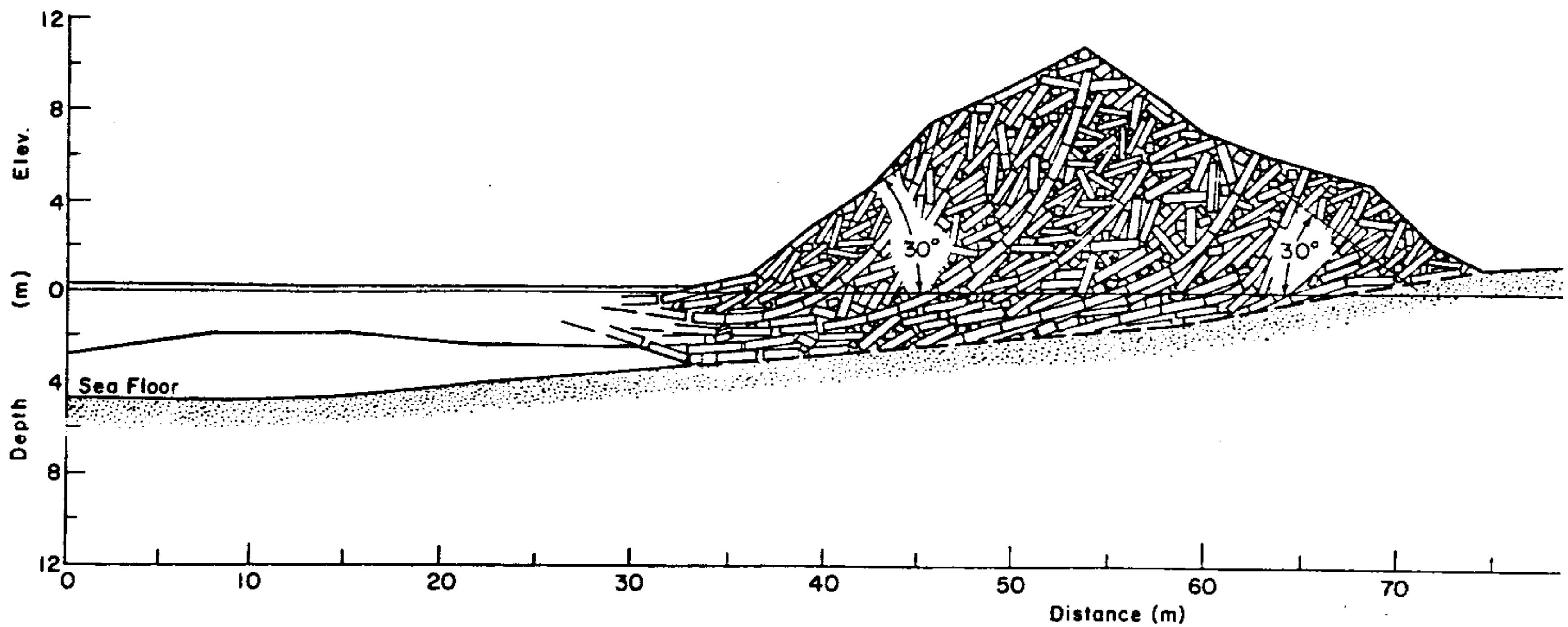


Figure 4-10. Cross Section of Shore Ice Pile-Up (modified from Kovacs, 1978)

More data on ice pileup and a better understanding of the causes and nature of this phenomenon are required for adequate structural design.

4. Ice Scouring

Ice scouring (gouging) is a potential hazard to any sea-floor installation including such things as pipelines, well-heads, and subsea completion systems. Fortunately, the hazard potential of this phenomenon has been recognized for many years and considerable effort has been expended to evaluate the problem by groups such as USGS, CRREL, and the Coast Guard.

A large quantity of information also exists for the Canadian Beaufort sector. Hnatiuk (1977), in a review of the Canadian data, has reported that the frequency of scour is greatest at water depths of 15 to 45m (50 to 150 ft). Most scours were found to be 1.2 to 1.8m (4 to 6 ft) deep with a maximum depth of 6m (20 ft) and width up to 305m (1,000 ft). Deeper scours were generally found in deeper water. The maximum scour frequency was 22 per mile and had directional trends parallel to the coast.

Kovacs (1972) reports that scouring in the Alaskan Beaufort was encountered in water depths up to 45m (150 ft) with a frequency of 15-20/km (24-32/mile). In deeper waters (>30m), scour depths up to 9m (30 ft) were observed, but these were believed formed when sea levels in the Beaufort were lower than today. Between water depths of 6 to 30m (20 to 100 ft), scour depths tended to be less than 1.5m (5 ft) but occasionally ranged between 3 to 4.6m (10 to 15 ft). In shallower waters less than 6m (20 ft) deep, scour depths did not exceed 0.6m (2 ft). Barnes and Reimnitz (1974) also noted that scour trends in the Beaufort were usually parallel to the coast.

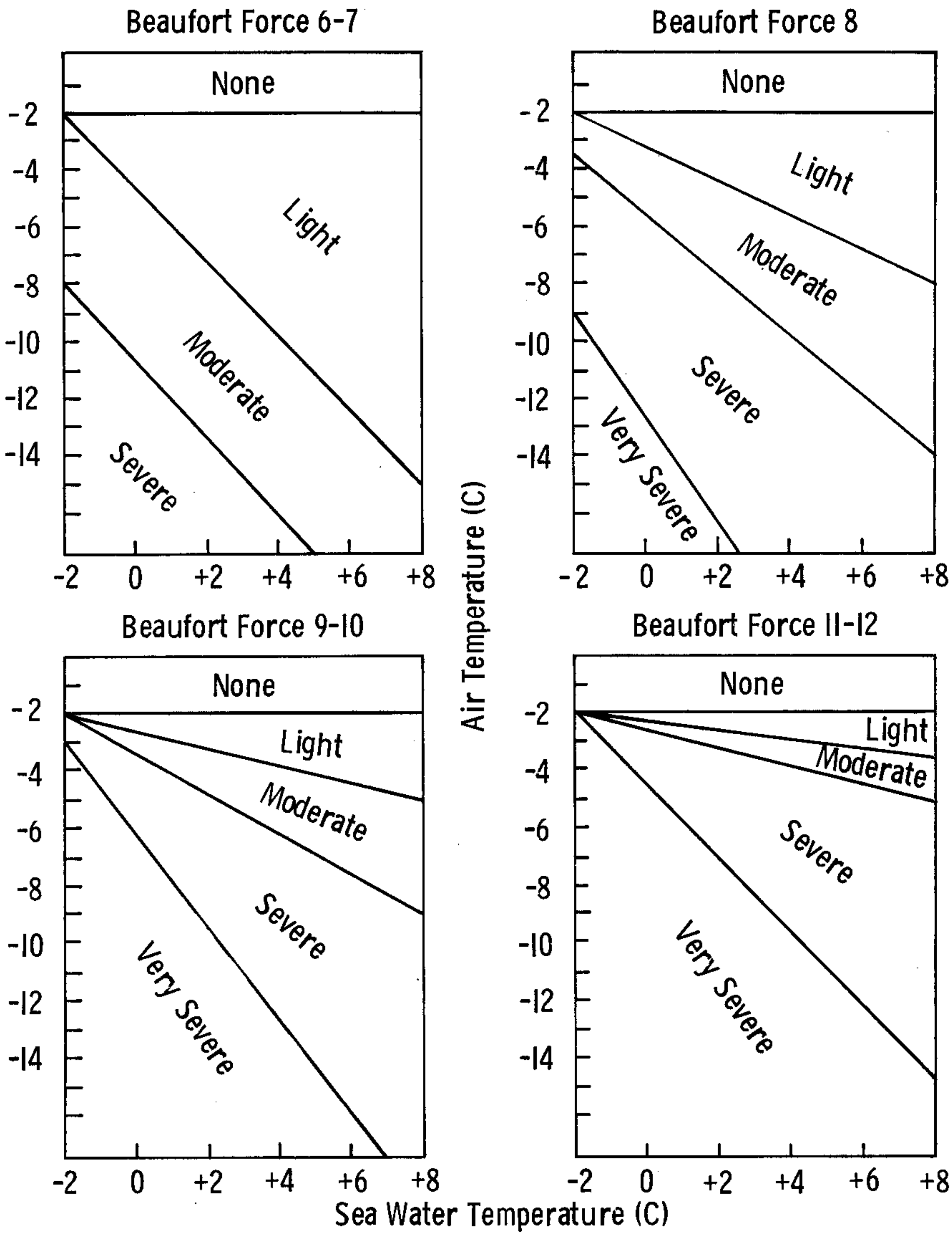
Toimil (1978), who studied scour in the Chukchi Sea, reports that the phenomenon appears to be patchy and less intense than in the Beaufort. The maximum observed scour depth was 4.5m (15 ft).

With respect to the design of seafloor installations, including pipelines, it is clear that some type of scour protection will be required at almost any location. If burial is used for this, installations in less than 6m (20 ft) of water may need to be placed a minimum of 0.6 to 1m (2 to 3 ft) below the mudline. At locations exceeding these depths, specific site studies will be required to determine the maximum probable scour depth. In water depths of 6 to 20m (20 to 66 ft), such burial depths may have to exceed 2m (6.5 ft) depending on location, bottom slope, and soil type. At locations in the vicinity of the grounded ridge zone, depths greater than 4m (13 ft) may be required.

5. Superstructure Icing

Ice accretion is a complex process which depends on sea and atmospheric conditions, and the nature of the surface upon which the ice is growing. Freezing spray is the most common form of icing. It can occur when the air temperature falls below the freezing temperature of sea water (usually about -2°C or 28°F) and when sea surface temperatures are below about 5°C (41°F). The lower the air temperature, and the stronger the wind, the more rapidly ice accumulates (Brower et al, 1978). Figure 4-11 illustrates the rate of icing as a function of wind, force and air and sea water temperatures. Icing studies in the Bering Sea and the Gulf of Alaska showed that maximum icing occurred in the rear of low pressure systems (McLeod, 1977).

In the Arctic, however, icing is not always a serious development hazard. The presence of ice, for example, will preclude the formation of spray except during the brief open water season. Also, air temperatures for this period are usually above freezing. Another factor, which limits the hazard potential of icing, is the expected nature of the development itself. Icing is mainly a hazard to vessels because it acts to elevate their center of gravity and interferes with maneuverability and speed. However, present indications are that initial development will proceed along the lines of artificial islands. Such structures do not appear vulnerable to icing.



Degree of Icing:	Light	1-3 cm/24 hr		Severe	7-14	cm/24 hr
	Moderate	4-6 cm/24 hr		Very Severe	15+	cm/24 hr

Figure 4-11. Icing on Fishing Vessels at Low Speeds in Winds of Beaufort Force 6-12 (McLeod, 1977)

B. OCEANOGRAPHIC

As pointed out previously, structures which are designed to withstand ice forces in the Beaufort Sea will, in general, be more than adequate to cope with the overall oceanographic forces. However, other factors, particularly erosion, by waves and currents, or overtopping by waves and tides, need to be considered in Arctic structural design.

As noted in the discussion in Section I.D, there is presently a data gap in our knowledge of the oceanographic environment, especially in the area of wave heights. Normal waves are known to be relatively small, seldom exceeding 30m (1 ft). Additional data would be useful regarding the spectral characteristics of those waves in order to provide better erosion control devices for artificial islands, causeways, and other structures composed of fill material. However, there is a greater need for storm wave data in order to design econonomical structures with adequate freeboard height to resist overtopping. Similar data are needed to evaluate the stability of monopods, monocones, and like structures. Major discrepancies presently exist in figures quoted for maximum wave heights. Values taken from the open literature (see Section I.D), range from 3 to 9m (10 to 30 ft). Clearly, resolution of these discrepancies is required.

Somewhat better agreement is found in the literature dealing with storm surge. Most authors report that a 3m (10 ft) surge is likely along the Beaufort coast at a recurrence interval of 25 to 100 years (see Section I.D.3).

Observations of currents, although sparse, are in general agreement as to the magnitudes which might be expected. Within the proposed Beaufort lease area, current speeds no greater than 50 cm/sec (1.0 kt) were measured in the OCSEAP program. The most probable speeds are in the range of 10 to 25 cm/sec (0.2 to 0.5 kt). Storm currents and inter-island currents will be greater.

C. GEOTECHNIC AND SEISMIC

The principal geotechnical consideration for petroleum development in the Arctic is probably permafrost. The presence of permafrost may affect foundation design, dredging, drilling operations, and pipelines. Permafrost is an observed feature of the Beaufort Shelf although its occurrence is quite patchy and difficult to predict. In shallow areas where ice rests directly on the bottom, ice-bonded permafrost may lie a few meters below the mudline. Vaudrey (1978) reports that near-surface permafrost may occur where the water depth is less than 1.5 to 2.1m (5 to 7 ft). In deeper waters, the permafrost level normally lies below 30 to 90m (100 to 300 ft). Hopkins et al (1977) suggest that relict permafrost may persist at water depths up to 90m (300 ft) but is probably absent in deeper water.

Most authorities agree that much of the present Beaufort permafrost results from a geological period when sea levels were lower. However, active formation of ice-bonded permafrost is still possible in coarse-grained sediments which have low salinity intergranular pore water. Since the bottom seawater temperatures typically range between -1°C to -1.8°C (30°-28°F), this is low enough to freeze fresh or slightly brackish water (Hunter et al, 1976).

In foundation design, the importance of permafrost will depend upon the type of structure and frozen soil. As an example, a sand/gravel island achieves a greater structural integrity as it freezes. It may, in fact, be advantageous for such structures to be bonded by natural or artificial freezing to underlying near-surface permafrost. Near-surface permafrost is a major impediment when island construction is done by dredging in the immediate vicinity of the site. Other bottom-founded structures, such as monopods or monocones which may transfer heat to the seabed, will have to be located either away from near-surface permafrost or insulated from it. Otherwise, thawing and subsidence may eventually result.

Permafrost is a hazard to drilling and production operations because of compressive and tensile stresses which may be generated in the wellbore by subsidence or freezeback. However, this problem was largely solved on the North Slope through the use of insulated or heavy-walled casings, and by the selection of appropriate drilling fluids. (A good series of articles on this subject by M. A. Goodman may be found in World Oil, October 1977 through May 1978). In offshore drilling this problem will be lessened because of the unlikelihood of freezeback.

Heated pipelines are especially vulnerable to permafrost since they may create a thaw bulb which allows the pipe to sag. A thermal analysis of a hot pipeline in permafrost done by Vaudrey (1978) showed that an uninsulated pipe would form a thaw bulb of 10m (33 ft) radius over a ten-year period. A properly insulated pipe would form a thaw bulb of only 0.3m (1 ft) during the same period. Thus it is apparent that thermal protection will be required for pipelines passing through near-surface permafrost, particularly in shallow water.

The effects and extent of frost heaving on above and below ground structures and facilities must also be considered. The influence of heaving, even on exploration drilling platforms, in terms of downtime or maintenance costs, can be significant and needs further identification.

A problem closely allied to permafrost is that of frozen gas hydrates which were found within permafrost formations. When heated during the drilling operation, the hydrates decompose and rapidly expand, creating overpressures and making control of the well difficult and hazardous. Although the distribution of gas hydrates is not well known, they are thought to be widespread on the Beaufort Shelf. Because of this possibility, great caution should be exercised in the selection of drilling equipment, drilling methods, and the training of personnel.

Seismicity on the Beaufort Shelf and in the Chukchi Sea has been studied by government, academic, and petroleum industry groups. Although not conclusive, these studies indicate that earthquakes should not be a major design consideration for Arctic offshore development. A few moderate earthquakes (Richter magnitude up to 5) are known to have occurred in recent years. These have all been shallow and have produced relatively small ground motions. Even if somewhat larger earthquakes were to occur, it is believed that the stresses generated in a structure would be smaller than those expected from ice movement.

The availability of offshore sand/gravel resources for artificial islands was the subject of discussion in Section I.E of this report. The data are at present sketchy and more location-specific boring test data will be required in the future. Additional geogechnical studies presently being performed in the lease sale area by the Department of the Interior during the 1978-79 winter season are expected to provide further insights on subsea geotechnical concerns.

D. CORROSION

If steel structures are utilized in Arctic development, it will be necessary to protect them from ordinary seawater corrosion and possibly from ice abrasion. Corrosion protection using either impressed current or sacrificial anodes is standard industry practice and should not present difficulties unique to the Arctic. The abrasion problem caused by ice friction is more unusual, although experience in dealing with Cook Inlet structures or with ice breakers, where a similar situation exists, probably can be applied to the Arctic environment.

V. POTENTIAL ENVIRONMENTAL EFFECTS OF OFFSHORE OIL/GAS OPERATIONS

The environmental effects associated with Arctic offshore development are the subject of many past and present studies. Several tens of millions of dollars have been spent so far in carrying out programs such as the Beaufort Sea Project, OCSEAP, as well as programs sponsored by industry (AOGA, APOA) and other interested groups such as the Arctic Institute of North America. Although a review of these studies is beyond the scope of this report, it is worthwhile to highlight some of the principal concerns and potential impacts which are associated with the new technologies and methods of operations in the Arctic.

This section begins with an investigation of the potential effects produced by structures that are likely to be used in Arctic development. It is followed by a brief examination of drilling and production activities. The section concludes with a review of special problems related to Arctic oil spills.

A. ARTIFICIAL SAND/GRAVEL ISLANDS AND CAUSEWAYS

The concerns associated with islands constructed of fill material center around the sources of fill, and the nature of its extraction and transportation to the construction site. Other concerns include the effects of the islands' presence on wildlife and the methods of abandoning an island.

The sources of potential fill material for artificial islands were reviewed in Section II of this report. It was noted that adverse and unacceptable effects may be caused by utilizing gravel from barrier islands, mainland beaches, or from rivers. Certain islands are very important in the breeding and nesting cycles of migrating birds, and some rivers, which remain unfrozen to the bottom, provide a winter refuge for a number of fish species. The mainland beaches are considered fragile with limited sources of sediment for replenishment. Use of beach material may also increase erosion rates along the coast. The most acceptable sources of fill material appear to be from the offshore Gubik formation or from thaw lakes located a kilometer (0.6 mi) or more inland. While the offshore sand/gravel source may be overlaid with thick overburden, there are dredges in existence, such as the Beaver Mackenzie and others which have the capability to dredge under 10m (33 ft) or more of silt.

The extraction of fill material, especially from offshore dredging sites, is expected to have some unavoidable but temporary effects. Most effects are associated with the burial or disruption of bottom communities by dredging or from fallout of the turbidity plume around the dredge site. Direct physical disruption will be limited to the dredge site and the dump site. Effects from fallout depend on a great many factors such as depth, currents, sediment size, etc.

Wright (1977) reported on Slaney's observations made in 1976, that with the exception of turbidity, the construction and dredging did not significantly affect the physical and chemical parameters mentioned.

Cox (1978) noted that benthic communities, one-third of a mile downstream from an island dredge site, did not differ significantly from those one mile upstream of the site. He also observed that the turbidity of a dredge plume is often less than the turbidity generated by summer storms. H. Feder and others at the University of Alaska, who have studied benthic communities in the Beaufort Sea, believe that ice is a natural, but severely disruptive feature in the benthic environment (Private Communication, 1978). Feder's observations suggest that organisms which have evolved in this environment may be considerably more resilient and less fragile than was once thought.

The transportation and general construction activity which surround an island site are a concern with respect to migrating wildlife, particularly whales and birds. Interference with natural navigation, communication, breeding, and nesting activity are postulated as potential effects although this has not been verified. Some measures will undoubtedly have to be taken to restrict activity at certain times or locations until these questions are resolved.

Artificial islands which will become operational are believed to have negligible effects in either drilling or production phases except for secondary problems due to noise and logistics which are discussed later. Islands may, in fact, produce some beneficial effects as stated by Wright (1977):

> "It is possible that islands may actually increase the amount of habitat available to fish. Some leeward effect would be created by the islands which may increase local productivity, as currents and eddies along the shore of an island may tend to concentrate non-mobile organisms and perhaps create a slightly more favorable habitat."

The abandonment of an artificial island raises some interesting environmental questions. Mechanical disruption or ultimate destruction of the island could cause similar or worse impacts than those noted for island construction. Very likely marine life would have adapted to or become dependent on the island's existence. Thus, it would appear inadvisable to destroy it unless it were a navigation hazard or unless the fill material is needed to be used elsewhere.

Causeways have many similarities to islands in that the construction materials and methods are expected to have similar effects. However, there are some additional concerns which center on the potential disruption of normal circulation patterns which causeways may affect. The nearshore circulation is believed to be important in providing sediments for beach replenishment and for distributing nutrients and other materials along the coast. Long causeways could disrupt this process. Potential effects might include enhanced erosion rates, reduced food supplies, and segregation of biological communities.

A considerable amount of research is now being carried out in connection with the Atlantic Richfield causeway at Prudhoe Bay. Originally built in 1973-74, this causeway was extended from a length of 1,250m (4,100 ft) to 2,750m (9,100 ft) in 1975. Questions such as those posed above are being addressed in these studies. If it proves necessary to mitigate the disruption of circulation along the coast, properly-designed and located bridges or culverts (Hopkins et al, 1978) may be used. It has been suggested that one of the incidental benefits of a causeway might be the containment or blocking of an oil spill (Hopkins et al, 1978). It seems reasonable to conclude that there are no major environmental issues connected with either artificial islands or causeways for which mitigating solutions cannot be found. It should be pointed out, however, that although the effects of a single project may not be serious, caution must be exercised in drawing similar conclusions about the impacts of multiple projects. Concentrating a number of islands within a small area, for example, may have cumulative or synergistic impacts which might not be acceptable.

B. NATURAL BARRIER ISLANDS

In the previous discussion of natural barrier islands as potential production platforms (Section III.5), it was noted that a number of islands have been identified as undesirable for this purpose because of their biological sensitivity as bird nesting habitat. These islands include: Howe, Duck, Niakuk, Gross and western Cooper Island. It has been suggested that these should not be recommended as possible production sites and that all except Niakuk Island be limited to winter exploratory drilling (Hopkins et al, 1978). It is also thought by Hopkins et al, that islands near Simpson's lagoon would be sensitive to drilling during August and September because they support large populations of nesting and feeding birds.

Regarding those islands which might be acceptable for drilling or production activity, there is some concern that efforts to stabilize them could limit their attractiveness to birds seeking shelter. Although measures could be taken to mitigate this effect, changes such as increasing freeboard or adding slope protection could be made so that slopes are less than 30^{o} to permit flightless birds access from the beach to the island (Hopkins et al, 1978). There is also some concern that the noise, traffic, and general activity surrounding a drilling operation would cause certain species to avoid the area. Consequently, noise abatement measures should be considered.

C. FLOATING OR GROUNDED ICE PLATFORMS

Since an ice platform is made from frozen sea water, the impact of the structure itself is probably no greater than any other natural ice feature. Furthermore, when the platform is abandoned, it will disappear without a trace.

The only apparent cause for concern is the sensitivity of these structures to lateral ice motion which may stress the riser during drill operations. Such an event could cause a shutdown or at worst, a well blowout or oil spill. This is particularly true of grounded platforms which are intended for use in shallow water. If a 6m (20 ft) riser were used, for example, it could not tolerate any lateral motion in excess of 0.3m (1 ft). Unless a riser or a ball joint is used, greater lateral motion could be allowed by some eccentricity of the drill pipe, or by skidding the rig. To avoid this hazard, drilling operations are usually limited to a period when the ice is thick and fast, the four months of February through May.

D. MONOCONES AND MONOPODS

The environmental problems associated with monocones and monopods are not fundamentally different from those of ice platforms except that some site preparation work might be required. Such work may entail dredging a pit for subbottom drilling components or building a foundation or pad for the structure itself. Relatively small areas would be affected by this activity.

As with ice islands, such structures are sensitive to lateral motion, although a different approach for dealing with ice forces is used. If these forces should become excessive, and some displacement of structure should occur, there would be a risk of equipment failure and a possible spill. To mitigate this risk, monocones and monopods would have to be equipped with subsea BOP's, quick disconnects, dual control safety valves, and other redundant safety features.

E. DRILLING AND PRODUCTION OPERATIONS

Environmental forces which impose stresses on offshore drilling operations lead to two types of hazard which have to be considered in design requirements: (1) safety hazards involving personnel; platform, drilling and production equipment; storage, and transportation; and (2) environmental hazards which involve construction, drilling operations, oil/gas spills, and waste disposal (Sackinger, 1977).

For a better understanding the design requirements for Arctic offshore operation, an in-depth analysis of environmental effects is necessary. Several studies were performed in the past on this subject by the Arctic Institute of North America (1975), the OCSEAP program (Synthesis Reports, 1977, 1978), Dames and Moore (1978), by the oil industry (AOGA, 1978) and by others.

To analyze the problem, the operational activities could be divided into exploratory, development, and production stages (Arctic Institute of North America, 1975) or into controllable and uncontrollable activities (OCSEAP, 1977, 1978).

It is thought that the latter is more suitable because the distinction in environmental effect between field development and field production may not be clear, while it will be much more distinct between controlled and uncontrolled situations.

Burns et al (1978) define the controlled activities as: establishment of settlements and support sites; on-site development and production structures (artificial islands, ice islands, gravity structures, etc.); transportation corridors including roads, piers, utility lanes, airfields, and storage areas; transport, supply and logistics; and disposal of drilling mud and waste.

The uncontrolled activities are defined as: gas or oil well blowout, major spills of crude oil including well failure or failure damage, fuel spills and facility fires.

The major possible effects of both groups of activities are discussed in this section with the exception of crude oil spills, and oil well blowout. See Section V.F for the latter subjects.

In general, potential effects of controlled activities may occur in the form of small, incremental changes in the environment. A few activities such as the building of structures or roads will result in noticeable, physical alterations of the environment. The main impacts, however, will likely be more subtle, and it may take many years before they are even recognized. Such things might include the alteration of migration routes or the displacement of organisms which are sensitive to human presence.

1. Establishment of Settlement and Support Sites

The construction of base camps, staging areas, and other support facilities along the Arctic coast may result in various types of habitat alteration. Small areas of tundra would be destroyed at construction sites and at other areas where tracked vehicles are used. Significant habitat damage may occur if gravel is removed from lakes or rivers. Gravel is commonly used for building pads in the Arctic and the most convenient sources are usually river channels and gravel bars because the problem of overburden removal is minimized. The removal of fresh water from beneath ice in lakes and river pools can, likewise, result in adverse impacts. In the winter months, these areas are not replenished until thawing occurs. Consequently, the drawdown of water levels may alter aquatic habitats. Other physical changes, due to establishment of settlement and support sites, may include thawing of permafrost, alteration of natural drainage patterns, reduction in air quality, petrochemical pollution, etc.

Habitation of onshore facilities may produce a variety of behavioral changes in resident wildlife species. The Arctic supports a great diversity of organisms, even in the winter months. Some of these animals are wary of humans and might be expected to disperse. Conversely, other animals such as scavengers are drawn to settlements in search of food. This, in turn, increases predation since other carnivores can find a concentration of prey species. Sometimes, these predators, such as bears or wolves, must be shot to protect lives and property.

2. Establishment of Utility or Transportation Corridors

The construction of roads, pipelines, airfields, piers, utility corridors, etc., will have many of the same physical impacts as described for settlements above. Unfortunately, the scale of these effects is usually far greater. Many more cubic yards of gravel are required to build a road or airfield than to build a construction pad for a structure. Likewise, more tundra is disrupted, scarred or displaced in the process. A similar problem holds true for utility corridors and onshore pipelines, either buried or elevated.

Beach construction such as piers or jetties may have temporary effects on the nearshore fauna. The construction of a submarine pipeline by trenching or jetting also would likely result in the disturbance of some benthic species. Recovery, however, would probably be rapid. During the winter months, the construction of snow roads or roads across the ice of offshore structures would have few, if any, adverse effects.

3. <u>On-Site Development, Drilling and Production</u>

Effects of on-site construction of platforms has been reviewed briefly in Section V.A. It was noted that the kinds of effects varied as a function of platform type. Normal operational activities, including drilling and production operations, would appear to pose no serious problems except for waste disposal, which is covered as a separate topic.

Undoubtedly there would be some noise pollution associated with drilling equipment, pumps, generators, compressors, and other devices. This might cause certain birds and marine mammals to avoid the structure. Some air pollution would also likely be generated as combustion by-products of machinery.

One potential problem which is yet unresolved concerns the source of water required for drilling and other platform operations during winter months. Structures which are situated in the bottom-fast ice zone may have no ready supply of either fresh or salt water. It is not clear if water requirements can be met by using thawed snow or ice, or whether it will be necessary to supply water from onshore facilities. If the latter is the case, an onshore source must be selected with attention to factors previously discussed.

4. Marine Transport, Supply and Logistics

Arctic development will require major logistic efforts. Supplies must be transported to the North Slope, stored, and then transported to construction or operational sites. Virtually all of the materials used except sand, gravel, and water will have to be imported.

It is anticipated that most bulk hauling will be done by barge or ship during the summer months. No impacts are foreseen from this activity except for slight damage to beaches and tundra during unloading and staging if this is done at some other place than Prudhoe Bay West dock. There is also the possibility of accidental discharges of cargo during transfers, and some petroleum pollution from bilge wastes. Such effects should be relatively minor, however, and could be controlled by careful operation.

The movement of personnel and materials from onshore to offshore sites may involve a great many modes of transport including boats, aircraft, air cushion vehicles, trucks, tracked vehicles, etc. Aside from the increased level of human activity which will accompany this movement, the readily identifiable effect would probably be in the form of noise pollution and air pollution. Noise sensitive organisms would probably avoid heavily used transportation corridors.

5. Waste Disposal

The elimination of wastes resulting from human or industrial activities is a serious matter in the Arctic. Natural degradation of organic wastes is an extremely slow process due to low temperatures. The disposal of solid and industrial wastes is usually an aesthetic problem but also may pose hazards to the environment.

Sanitary and solid wastes are the principal by-products of onshore activities. Indiscriminant disposal of sanitary wastes into rivers, lakes, and streams can pose water pollution problems affecting aquatic life. Solid waste disposal, especially in the form of garbage, empty cans, bottles, etc., in open unsecured dump sites may draw a variety of undesirable wildlife to the vicinity of settlements. Unfortunately, waste burial is generally not practical because of the difficulties of working in permafrost. The burning of some materials is possible but the remainder has often, in the past, been consigned to the tundra forever. However, the experience gained in the Prudhoe Bay development should provide useful guidelines.

At offshore sites, the disposal of sanitary wastes may be accomplished by direct dumping into the sea, if sufficient water is available for flushing and dilution. The presence of ice at certain times will probably preclude this. Wastes may have to be held, incinerated, or chemically treated if no other methods of disposal are possible. Typically, self-contained, portable treatment plants now in existence provide secondary treatment of sanitary wastes.

One of the offshore problems is the disposal of drilling muds and cuttings and this was dealt with in considerable detail in both the report of Arctic Institute of North America (1975) and the OCSEAP Studies (Burns et al, 1978). Drilling muds may be oil or water-based and may contain a variety of toxic materials (heavy metals, bacteriocides, etc.). Drill cuttings, although not usually toxic, are considerable in volume and weight. It is estimated that a 3,000m (10,000 ft) well would produce a volume of cuttings amounting to 2,500 to 3,000 barrels (Burns, 1978). When wells are drilled using water-based drilling fluids, the cuttings and mud are usually discharged overboard where they are dispersed and detoxified by dilution. In shallow Arctic waters, however, this disposal method may not be practical since the cuttings would not disperse and would accumulate on the bottom. Other disposal options include onshore dumping or transporting to deeper waters offshore. Onshore disposal is questionable because of potential leaching of toxic materials into the soil. Offshore dumping may be safer and more practical because the material could be deposited on ice and would be dispersed during spring break-up.

Oil-based mud and cuttings disposal are regulated by the USGS and the EPA. Dumping at sea is not permitted and cuttings must be disposed of at suitable onshore sites. It is not clear what the best alternative will be for Arctic disposal. Neither onshore nor offshore dumping appear desirable. Other alternatives may include burning or reconditioning. Fortunately, oil-based muds are not used as extensively as water-based products since they tend to have special applications mainly in workover operations during production.

The category of uncontrolled or unplanned activities which involve petroleum development include a variety of effects, which vary in severity from negligible to major. Unlike scheduled activities, unplanned events occur with a much lower frequency. Because of their potential severity, however, it is necessary to include them in any consideration of environmental effects.

a. Fuel Spills

Fuel spills are among the most common type of accidents associated with petroleum development. The severity of impact varies with size of the spill, time of year, and success of any clean-up effort (Burns et al, 1978). In general, fuels such as gasoline and diesel oil are more toxic to living organisms than crude oil. If subjected to significant concentrations of spilled fuel, most organisms ranging from plankton to birds and mammals will die. Even brief contact can be lethal. Spills which occur on waters in summer are far more serious because of the high concentrations of aquatic organisms and the general intensity of biological activity which occurs during this period (e.g., feeding, nesting, spawning, etc.). Winter spills on ice are less apt to be serious because they do not disperse rapidly and can readily be cleaned up.

Fuels tend to have a high proportion of volatile fractions which normally evaporate within several days. The remaining and less toxic fractions can be incorporated into beaches and sediments. Some may be ingested by lower organisms and find their way into the food chain. If a spill is large enough or if it is a small, but chronic problem, petroleum products may be spread to higher trophic levels and perhaps concentrated by some species. The long term effects of this process are not well understood but are believed by some authors to be significant. Some of the impacts which have been postulated include suppression of reproduction, changes in growth rates, carcinogenic effects, behavioral changes, and direct mortality (Burns et al, 1978).

In general, it is likely that fuel spills would not be large and that effects would be highly localized. The major exception to this might be a spill from a supply tanker.

b. Gas Well Blowout

A gas well blowout per se would probably have little effect on aquatic habitats or organisms (Burns et al, 1978). Most gas would be released into the atmosphere. Soluble components which may be incorporated into seawater have relatively low toxicity. Secondary occurrences, such as cratering at the drill site, destruction of rigs, loss of materials and subsequent repair or reconstruction activity would be the apparent consequence.

c. Petroleum Facility Fires

The probability of facility fires, although not normally high, may be greater in the Arctic because of the additional requirement that a variety of heat sources be used for men and machines (Burns, 1978). Facility fires normally involve gas or a mixture of gas and small volumes of crude oil. Occasionally a fire will involve crude oil as the major component.

A gas fire would probably have less effects than those indicated for a gas well blowout and could be brought under early control. If crude oil is involved, the effects may be greater and geographically more extensive (Burns et al, 1978). Some authorities think the burning of oil would intensify spill problems by creating higher concentrations of nonflammable but toxic components in the vicinity of a fire. It is believed that some of the heavier components would sink and become incorporated in the sediment in much higher concentrations than those resulting from a dissipated oil spill. The effects of this phenomenon on living organisms would be similar to those indicated for fuel spills.

F. MAJOR CRUDE OIL SPILLS - WELL BLOWOUT

1. Background

Crude oil spills generally occur as a result of tanker accidents, well blowouts, or transfer equipment (e.g., pipelines) failures. Tanker accidents account for the majority of serious spills. However, the use of conventional tankers for crude oil transport in the Arctic does not appear imminent because of the hazard involved, and because the Trans-Alaska Pipeline would offer a safer and probably more economical alternative. Well blowouts, involving the loss of control over the well discharge, are a possible source of major Arctic crude oil spills. It should be pointed out, however, that the statistical probability of such an event is very small. Kash et al (1973), reported that of all wells drilled in the period 1964-1971, only 0.03 percent experienced gas or oil blowouts. Nevertheless, limited drilling experience in offshore Arctic geologic formations, coupled with the knowledge of potential hazards (e.g., permafrost, gas hydrates), suggests that well blowout must be addressed as a possibility. According to the same statistics, most of the blowouts occurred during the production and not during the exploratory drilling phase. Also, exploratory drilling blowouts recorded were associated with gas rather than with oil release.

Transmission pipeline failures occur very infrequently and normally result in small losses of crude oil. In the

Arctic, however, such equipment may be more vulnerable to damage because of potential hazards such as ice scour and permafrost.

The problem of oil spills in ice-covered waters has been studied by numerous researchers. The methods employed include laboratory tests, _in situ_ field tests, analytic techniques, and reviews of accidental spills. The following is an annotated listing of typical studies:

a. Beaufort Sea Project (1976) - reviewed the fate of oil spilled in the offshore Arctic.

b. Burns et al (1977, 1978) - well blowout scenarios in the Beaufort Sea.

c. U.S. Coast Guard (1971) - _in situ_ oil release and oil recovery by burning near Point Barrow.

d. Hoult (1975) - analytic and laboratory work of oil spreading over and under ice.

e. Lewis (1976) - experiments on oil accumulation under ice.

f. Logan (1975) - oil spill countermeasures in the southern Beaufort Sea.

g. Norcor Engineering (1978) - field tests in a small bay east of the Mackenzie River.

h. Pimlott (1976) - reviewed impacts of oil on Arctic ecosystems, the behavior of spilled oil, and clean-up methods (burning of oil was found to be a good disposal method).

i. Ruby et al (1977) - described Buzzards Bay, Massachusetts oil spill and clean-up attempts.

j. Allen (1978) - described an accidental oil spill in Nome, Alaska.

k. Ray (1978) - oil spill response, fate and effects in the marine environment.

l. Westeng et al (1977) - oil spreading computer program (OILSIM) used in North Sea spill.

m. Arctic Institute of North America (1975) - scenarios of Arctic offshore blowouts and time schedules to recover well control.

n. Schultz et al (1978) - systems for Arctic spill responses.

This listing, although not complete, illustrates the range of interests in the subject. Unfortunately, the net result of this work to date is that a great deal is known about the potential behavior of oil and ice, but there is no clear strategy yet for dealing with oil containment and clean-up problems. The federal government has not yet formulated contingency measures for large spills in the Arctic Sea but the industry (AOGA) is developing a plan (ABSORP) under a cooperative effort. The absence of such a plan could result in a major impact as was recently illustrated by the Amoco Cadiz tanker accident off the coast of France.

2. The Effects of Spilled Oil

One of the unique difficulties in containing an oil spill in the Arctic Sea is the great seasonal variation in ice morphology. In winter (November to April), the oil lease areas are covered with thick landfast ice reaching seaward to the shear zone. During the spring (May to July), when ice break-up occurs, the ice starts moving and free water appears. During the summer (August to September), the ice pack retreats and a zone of open water appears along the coast. In the freeze-up period (October to November), landfast ice is gradually formed, increasing in thickness with time.

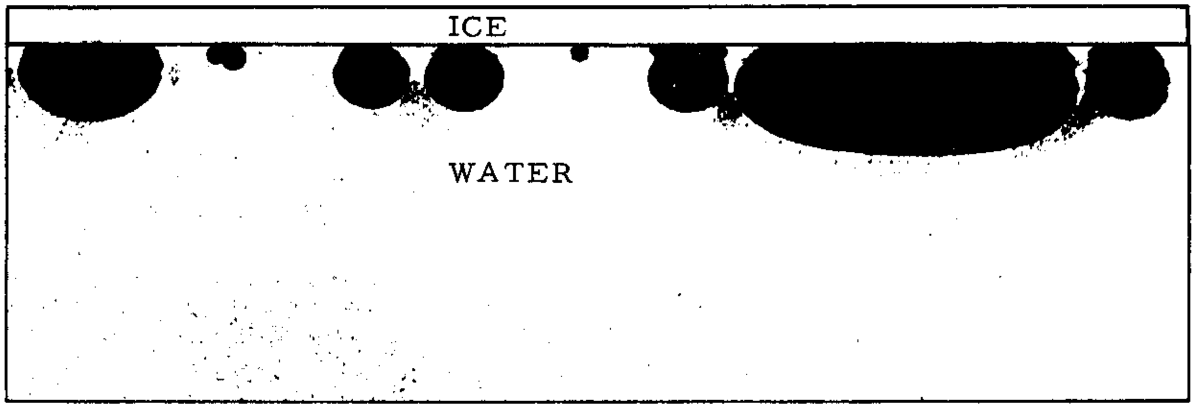
The winter situation is probably the least serious with respect to impacts since spilled oil is confined to the upper surface where control and clean-up are relatively easy. It is likely that only animals which come in direct contact with the oil such as seals or polar bears, would be affected immediately. If the ice is covered with snow, the dispersal of oil may be slowed since snow can absorb as much as 25 percent oil (Glaeser, 1971). One of the principal concerns of an over-ice spill is that the oil would reduce the ice albedo, causing it to melt in early spring.

A winter spill under fast-ice would be subject initially to gravitational and viscous forces. Because of low temperatures, oil is a highly viscose which causes it to spread slowly in thick layers. Lewis (1976) found that globules of oil rising from the spill source coalesced into a thick layer as shown in Figures 5-1 and 5-2. Hoult (1975) found that such a layer is normally about 6 mm (1/4 in) thick. Another factor controlling under-ice spills is the morphology of the lower ice surface. Since the surface is normally rough, oil can collect in cavities and crevices. Consequently, fairly large volumes of oil may be contained in a relatively small ice surface area. A graph shown at the bottom of Figure 5-1 illustrates the spread of an under-ice spill as a function of time with oil film thickness of 8 mm (1/3 in). The "standard" blowout used for the calculation consisted of 2,500 barrels/day for one month, and 1,000 barrels/day thereafter.

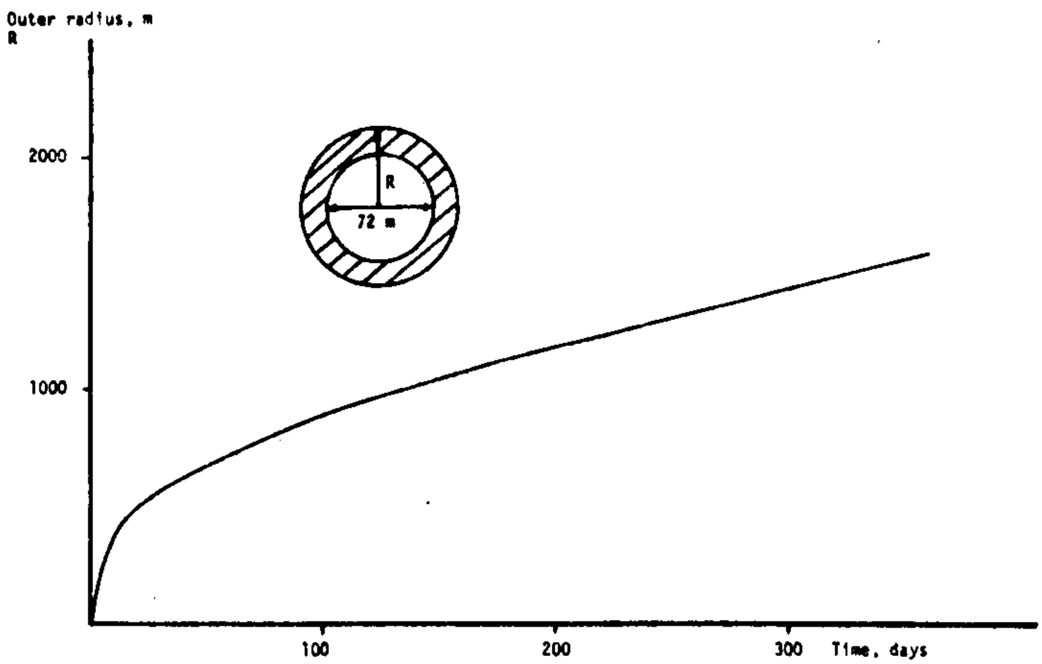
Ice may continue to grow downward beneath the oil surface if a spill should happen in the late fall or winter before maximum ice thickness is achieved. As a result, the oil may remain sandwiched between ice layers until thawing occurs.

The effects of a spill under ice will probably be relatively slight while the oil is contained in or under the ice. Seals, plankton, and fish would suffer if exposed to the oil but it is not likely that significant numbers would be involved. The major problems would occur when the spring thaw begins in May.

Oil remaining from a previous under-ice spill or oil which occurs as the result of a spill during the spring months presents a more difficult problem. As the ice melts, oil would



CRUDE OIL DROPS BENEATH A SEA ICE SHEET. THEIR SHAPE IS THE RESULT OF A BALANCE BETWEEN HYDROSTATIC AND SURFACE TENSION FORCES



RADIUS OF THE OIL CONTAMINATED AREA UNDER AN ICE SHEET AS A FUNCTION OF TIME FOR THE "STANDARD" BLOWOUT

Figure 5-1. (Lewis, 1976)

Figure 5-2. Rivulets of Oil Flowing Under the Sea Ice from One Depression to Another (Lewis, 1976)

float to the surface and expand to fill the spaces left by melted ice. In the areas near river mouths, oil could be dispersed by the spring run-off, and some of it would sink as a result of mixing with river-borne sediments. Oil entrained within unmelted ice may be transported great distances as break-up continues and ice floes begin to drift away from the original spill area. With the arrival of summer it is likely that the surface distribution of oil would be patchy. A considerable amount of oil will have evaporated by this time; the remainder will be dispersed in the water column, sediments, or washed up on beaches.

The biological effects of a spring spill would depend greatly on timing. A spill occurring in April would only retard photosynthesis by reducing light penetration. A spill in May or June would be more serious since this is the period when migrating birds and whales begin to appear, and a great many plankton and fish reproduce and begin to feed. Seals also become more numerous in the Beaufort Sea in late spring.

A spill during the summer ice-free months is not fundamentally different from a spill in temperate waters with regard to the behavior or fate of oil. The potential effects, however, can be more significant. Initially, a summer spill would be subject to dispersion by winds and currents. Some organisms coming into direct contact with the floating oil, especially birds, would be affected. Within one or two days, the lower molecular weight fractions would either evaporate or dissolve in the water column. Dissolution could affect larval plankton and fish and reduce the reproductive capability of adult fish, plankton, and benthic species.

Within one or two weeks, the visible portion of the remaining oil would be found as discontinuous slicks, or piled against the shoreline, perhaps as a thick emulsion. Bird mortality might continue during this period, but direct mortality to other aquatic species would decrease.

On a longer time scale, some of the oil would sink and become incorporated into bottom sediments and beaches, or a portion may be trapped in offshore ice. Of the remaining oil, a large part would be broken down by bacteria eventually. Other oil may enter the aquatic food web with possible consequences similar to those of fuels which were described previously.

If oil is still present during the freeze-up, or if a well blowout occurs during that time, oil will remain on top of the ice. Ice will continue growing under it, albeit at a reduced rate, because of the insulating effect of the oil.

Summarizing this discussion, there is one factor which is in favor of an oil spill in the Arctic as compared to a spill in milder climates: the effect of low water and air temperatures limit oil spreading to viscosity and gravity forces only, allowing it to remain in a relatively thick layer, thereby reducing the area of spreading.

3. Fate of Spilled Oil

The oil discharged into the environment undergoes a weathering process. Figure 5-3 illustrates this process which consists of spreading, evaporation, emulsification, dispersion, dissociation, chemical reaction, and biodegradation (Arctic Institute of North America, 1975).

To obtain an idea of the fraction of the oil spilled involved in these various processes, it may be of interest to quote the data obtained from the March 1978 oil spill from the tanker Amoco Cadiz. Of the 220,000 tons of crude oil released, over 30 percent was lost by evaporation, approximately 25 percent mixed with silt due to storm-caused turbulence and settled at the sea bottom, about 15 percent emulsified and mixed with water, and approximately 25 percent was recovered. In the Arctic conditions, the balance would be different because of differences in climate and in crude oil composition. With the spill under ice, there would be no evaporation and even with the surface spill, the loss by evaporation, with the exception of summer months, would probably not exceed 10 to 15 percent.

Oil spilled under ice will undergo few immediate changes with the passage of time. Some of the low molecular weight hydrocarbons will dissolve posing a hazard to plankton, fish larvae, and small invertebrates. Evaporation is effectively precluded by the ice surface and biodegradation is slowed by

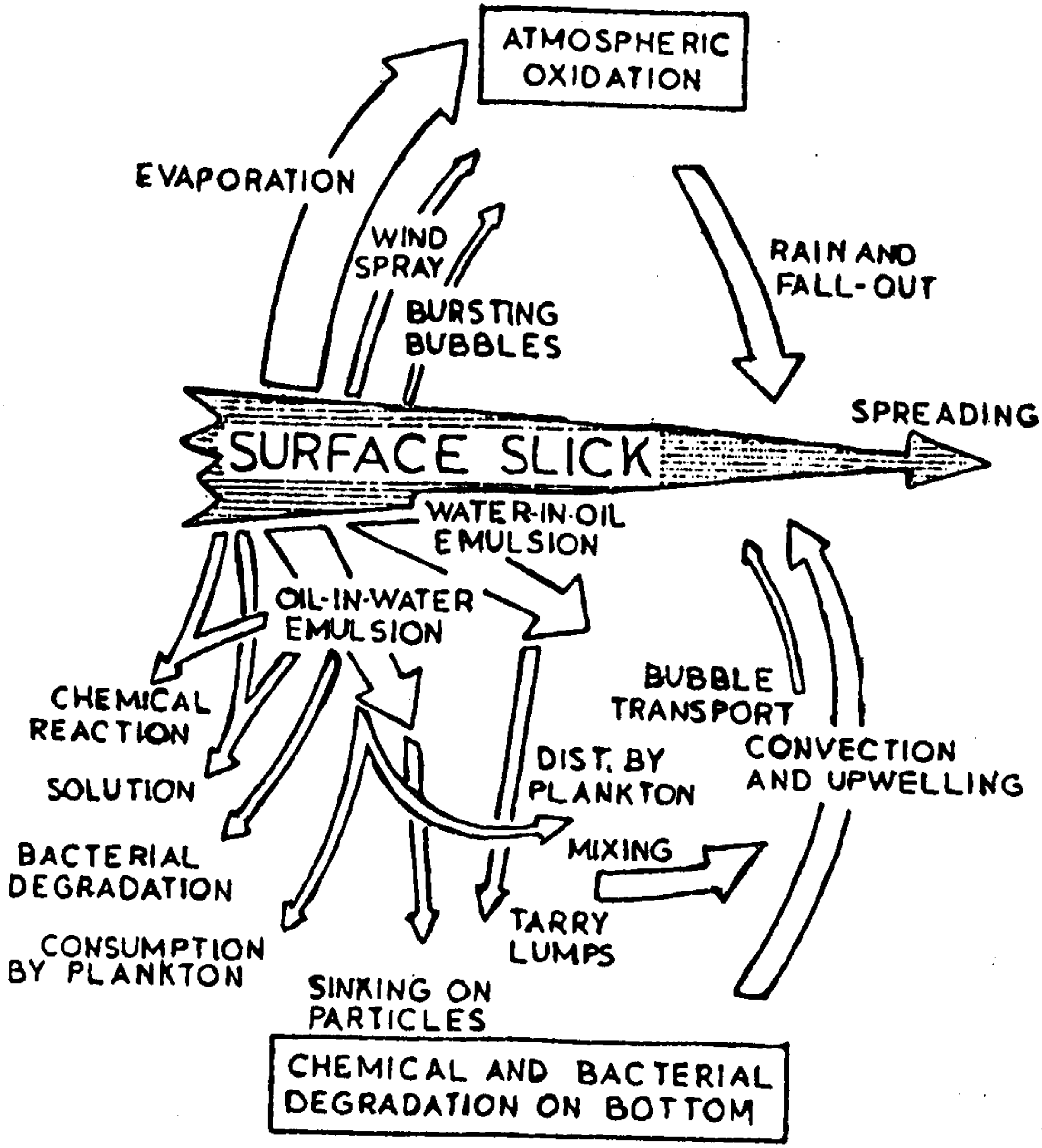


Figure 5-3. Factors Affecting the Spread and Weathering of Oil on Water (Arctic Institute of North America, 1975)

cold temperatures although there is new evidence that it still may be significant even under Arctic conditions. A portion of the oil will become entrained in brine channels and the skeletal layer of the lower ice surface.

The amount of oil which could be recovered in the Arctic condition would probably not exceed 30 percent, as evidenced by a small spill in Nome, Alaska, in which an all-out effort succeeded in a recovery of approximately one-third of the oil released. In the Buzzards Bay oil spill incident (Ruby et al, 1977), only 12 percent of the oil was recovered by burning and suction collection. Thus, of the remaining 50 percent of oil, 2 to 10 percent would form tarry residues (Glaeser, 1971) and the rest would be lost by biodegradation, by emulsification, or by diffusion into the sediments. Oil biodegradation remains effective even at low temperatures, as reported by Ray (1978).

4. Oil Spill Countermeasures

a. Planning

A fundamental prerequisite for dealing with major spills is the contingency plan developed specifically for Arctic regions. There is presently a national plan, prepared at the direction of Congress in 1968, which provides a general mechanism for coordinating the response to oil spills or other hazardous materials. However, a specific regional adaptation of this plan is required for offshore areas of the Beaufort and Chukchi Seas. The industry (AOGA) is working now on such a plan which would define the following functions:

(1) The responsibility and organization of spill containment and clean-up activities

(2) Equipment needs and availability

(3) Manpower requirements and availability.

This plan should provide for close coordination between responsible government agencies and industry. It should also contain a realistic schedule for implementation. Since all spills tend to be unique, a contingency plan must provide enough flexibility to allow for initiative and improvisation, but at the same time, be specific enough to be of practical value to the blowout team.

b. Spill Evaluation

One of the first problems to be dealt with in any spill is defining the magnitude of the spill, including the rate of oil release, direction, and area of spreading. Various techniques such as radar, microwave, and lasers have been developed to aid in the surveillance of spills (Shafer, 1978). Most methods are limited to situations where oil is on the surface of either ice or water. Through-the-ice surveillance capability other than by drilling is not yet available. Computers can be useful in predicting the movement of oil. A number of stochastic models have been developed for open water and ice spills. The presence of ice makes oil movement prediction complex and consequently prediction is less precise (Shafer, 1978).

c. Containment

The containment of a spreading spill and the protection of environmentally sensitive areas has a high priority in any spill situation. In open waters, booms of various types have been used with differing degrees of success. Booms are not very effective in waves greater than 1m (3 ft) high. High sea states are fairly rare in the Arctic, and booms should provide a reasonable solution to open water containment.

Logan (1978) has suggested an ice retention boom for spills involving water and floating ice as might occur during spring break-up. This concept would involve a double boom arrangement whereby an inner boom would be used to contain oil and an outer boom would be used to resist encroachments by floating ice. The booms would be deployed as polygons around a drilling platform and would be designed to remain in place throughout the winter months.

For over-ice spills, artificial ice barriers would probably be effective in retaining oil (Shafer, 1978). Under-ice spills may be contained with booms lowered through slots cut in the ice. Alternatively, it may be possible to develop a containment boom which offers both over- and under-ice protection. Such a boom would need to be about 3m (10 ft) high and would be deployed around a platform prior to freeze-up. If a spill occurred, either above or below ice, spreading would be prevented by the upper and lower edges of the boom. Gerwick (Private Communication) mentions plastic booms, normally seated on the sea floor around the drill site, which could be air-lifted to provide an under-ice fence for containing the spill.

d. Recovery

Various devices and methods have been developed for oil recovery and some have been tested for Arctic use. Oleophilic disc-drum skimmers have been found to be effective in the presence of floating ice up to 3m (10 ft) in diameter (Shafer, 1978). Oil trapped under ice may be partially removed by pumping, although a significant fraction would be retained in small cracks and crevices. Snow is very effective as a jelling and sorbent agent for oil and could be used for over-ice spills if sufficient quantities were available. Other sorbents such as straw are also quite effective. It has been found that 15 pounds of straw may absorb as much as 17 gallons of oil (Glaeser, 1971).

Oil burning was also found to be effective in some cases, and the thicker layer of oil formed in icy waters makes this process easier to implement. Although maximum recovery of a spill is usually the preferred strategy, it is sometimes desirable to use dispersants, emulsifiers, or burning as a means of dealing with spills. The methods utilized depend on the characteristics and circumstances of a particular spill. An oil spill contingency plan should provide guidelines for the use of alternative methods.

e. Storage

Oil which is recovered must be stored temporarily to await disposal or reclamation. Potential storage can be provided by steel tanks, pillow tanks, barges, or banked containment areas (Shafer, 1978). Storage containers may be located onshore or on ice if it is thick and stable.

f. Disposal

Many options are available for disposal. These include burning, injection into a subsurface formation, burial, or reclamation. Burning should be done by the use of incinerators to reduce the amount of air pollutants. Logan (1978) has suggested that barges could be useful in a reclamation effort since wastes could be both stored and processed in the same facility.

g. Summary

Offshore Arctic development will impose a variety of physical and biological impacts on the natural environment. With careful planning, the majority of these can be anticipated and their effects mitigated to acceptable levels. Most impacts are of a transient nature and complete recovery could be expected within a brief period. Other impacts such as those associated with major spills may be longer lasting and perhaps irreversible. Major gaps exist in our knowledge concerning the behavioral changes in organisms which may be produced by an increased level of human activity in the Arctic. Some of these gaps are discussed in Section VIII of this report. An important one is our lack of understanding concerning the long term, sub-lethal effects of petroleum on the marine environment. Because of this, stringent measures will be required to avoid oil spills. Moreover, methods and plans for coping with spills must be brought to a condition or readiness before development of any large-scale offshore oil field.

VI. OVERVIEW OF HAZARDS TO EXPLORATORY DRILLING CONCEPTS

This section presents a summary of the hazards to and design countermeasures for, shallow water drilling concepts.

A. ARTIFICIAL SAND/GRAVEL ISLANDS

The sand/gravel island is, in general, a massive structure consisting of hundreds of thousands (or even millions) of cubic yards of sand and gravel and can resist most external forces effectively. The integrity of sand/gravel islands can be adversely affected by wave action, bottom instability, currents, and ice forces. Storm waves in summer months can be the most damaging. They can cause severe erosion of unprotected beaches, resulting in the loss of large portions of the island. If waves are high enough, they could overtop the island and damage some of the structures. There is little information on storm waves; consequently, predicting a recurrence interval may be difficult. As a result, the island's freeboard may have to be overdesigned to compensate for this uncertainty.

Bottom stability and the effects of currents are characteristics that can be measured in a preconstruction survey and therefore, protective measures such as moving to a different site can be taken. However, ice forces introduce another variable. Large ice features, or moving ice islands that could normally destroy some structures, will become beached on the island slopes or in the shallow waters of the Beaufort Sea OCS and, therefore, are not considered a significant hazard. Among the ice actions, ice override is considered of some importance as it could ride up slopes and push over the top of the island enough to damage facilities and equipment. This phenomenon, like summer storm waves, is difficult to predict. It is known from experience that careful design and maintenance of the beach slopes is critical in protecting against both wave and ice override activity.

The following are some of the fundamental design features that sand/gravel islands should incorporate to counter the threats of wave and ice forces:

1. The geotechnical properties of the fill and of the seabed should be well-known, and the fill should have sufficient shear strength to withstand ice forces. If necessary, artificial freezing, utilizing such means as heat pipes, may also serve to enhance fill strength and erosion resistance characteristics.

2. Slope protection, based on experience already available, should be adopted to withstand wave action for either short-duration (exploratory drilling in summer) or long-duration (production).

3. Freeboard should be sufficient to prevent flooding of the working area by a 10-year storm wave (exploratory

drilling in summer) or by a 100-year storm wave (production), and to protect against ice override.

4. Detailed inspection and maintenance plans for long-duration islands should be prepared for the assessment and repair of wave erosion and ice damage.

5. Barrier structures or submerged jetties may be constructed so as to restrain major ice features and allow minimization of island sizing where several islands would be needed for production purposes.

The requirements listed above imply the availability of some statistical data for ice movement, ice override, and for storm waves at a given location. Water depth does not appear to be a technological constraint in island location. Instead, the constraint is economic and is related to the volume of fill required and its availability.

It appears imprudent, in the immediate future, to build islands beyond the 13 to 20m (50 to 66 ft) water depth because there is insufficient knowledge of both ice movements in deeper waters and the forces associated with ice ridges that begin to appear. The Imperial Oil experience with the Isserk Island in 13m (43 ft) of water, and with the island recently completed in 19m (63 ft) of water will be of assistance in future decisions regarding the practical limit of water depth for sand/gravel islands.

With regard to the environmental impact of sand/gravel islands, the greatest impact as discussed before, will be caused by the dredging of the fill. A summary of fill availability was given in Table 2-4. From this it can be concluded that the two environmentally acceptable sources are the seabed and onshore gravel pits. The effect of sea bottom dredging on benthic organisms and water turbidity is overshadowed by water turbulence, and seabed plowing routinely caused by storm waves and ice scouring.

Once an island is built, its existence per se would not have any significant environmental impact. When an island is abandoned, it may be preferable from the environmental aspect to remove the slope protection and to allow it to be eroded gradually by wave and ice action. However, a final decision will depend on ice location, the type of fill material and on the life of the island.

B. FLOATING ICE PLATFORMS

The main hazard to this type of drilling platform is excessive ice movement. So far, floating ice platforms have been considered only in sheltered areas where the ice motion is constrained. Therefore, this concept should be restricted to a special set of conditions; such as when the water is deep enough, say, above 60m (197 ft) and the area is protected by nearby islands so that the ice movement during the drilling season does not exceed 5 percent of water depth. Since such conditions exist in the Canadian Arctic Islands, Panarctic Oils were able to use this concept for exploratory drilling.

However, such a platform would not be suitable for offshore in the Beaufort Sea OCS, where exploratory drilling will be considered in the near future, because of frequent ice movements greater than 1m (3 ft).

C. GROUNDED ICE PLATFORM

Grounded ice platforms such as the one built by Union Oil, have a distinct possibility for Beaufort offshore in shallow waters equal to or less than 4m (13 ft). The water depth limit results from the thickness of ice which can be built up by flooding during a winter season leaving sufficient time to complete drilling before the end of April. The major hazards to this type of drilling platform are sudden ice movement and degradation of ice strength during thaw periods.

Sudden ice movement can cause the ice platform to shift, depending on how well the island is grounded. The effects of such occurrence could be reduced by maintaining a moat around the platform to avoid contact with the ice sheet. The additional hazard of degradation of ice strength during thaw periods could be countered by removing the drilling equipment before the thaw period begins. As a result of these concerns, the following features should be incorporated in plans for grounded ice platforms.

1. A concept such as a moat or other protection should be included in the design to prevent direct contact between the ice platform and the ice sheet. Techniques for maintaining the moat or other protection during the winter must be reliable.

2. Predictions and/or real time measurements of ice movement should be available to predict or detect sudden movements. In general, this means better weather information on storms and location of instruments in the ice sheet around the platform.

3. Time schedules for platform construction and drilling should be realistic and conservative so that the well drilling is completed and drilling equipment removed before ice strength degrades appreciably and ice movements become large in the thaw period. Utilization of the recently developed ice aggregate construction systems, possibly in combination with flooding techniques, may allow acceleration of island construction, thus providing longer drilling periods.

4. A quick disconnect or a BOP should be installed below the mud level so that a well can be safely secured in case of emergency.

At present, grounded ice platforms can be considered only for exploratory drilling. Whether one can build an ice platform of sufficient bulk to survive the summer remains to be seen from the experiment planned by Exxon and mentioned earlier in this report. Recent experience with ice aggregate work pad construction on the National Petroleum Reserve project may also provide some additional insights as to the appropriateness of using ice aggregate (Fisher, 1977).

The environmental disturbance caused by a grounded ice platform is negligible. The construction material is seawater, and when the platform is abandoned it would usually disappear before the end of the summer unless special measures are taken for its summer survival.

D. MONOCONES AND MONOPODS

It is unlikely that monocones or monopods will be used for initial exploratory drilling in the Beaufort Sea for three reasons: first is that neither monocones nor monopods can be conveniently used in shallow waters less than 6m (20 ft) deep; second, experience is lacking with these types of structures in icebound waters; and third, other proven systems exist which require less lead time and investment.

The main hazard to the monocones or monopods will be ice forces which could induce high static and dynamic stresses. If these structures are placed in the ice shear zone for a period of years, collisions with multi-year ridges and consequently high ice forces are inevitable. Most monocones and monopod platform designs could have provisions for grounding large ice features or deep keel pressures on a subsea berm. As long as this practice is used the large ice feature may not be a threat. However, resisting the not grounded ice could cause vibrations and could pose a challenge in design and materials.

Following are features that should be considered and could be incorporated in designs for monocones and monopods.

1. Provisions should be made for grounding deep-keel ice ridges before they collide with the structure if the ice force prediction is not adequate. This could be done, for example, by constructing a protective berm around the base of the structure high enough to ground deep-keel ridges;

2. Structure natural frequency should be outside the range of vibrations caused by invading ice;

3. Materials with high fracture toughness at low temperatures should be considered for structural members subjected to fatigue loads;

4. Sufficient structure freeboard should be provided to prevent overriding by ice;

5. Design guidelines should be made for ice sheet and ice ridge forces, and for ice strength applicable to local conditions.

It might be desirable that a prototype monocone and monopod structure be built, instrumented and installed in the landfast zone or in the ice ridge zone (if the design is adequate) for one or two years to obtain data on ice forces and structure survival.

The environmental impact of a structure itself would be minimal particularly if a protective berm is not required. It would be constructed elsewhere, it would be towed to a location, and set on the seafloor during a summer season with only a small disturbance to the seafloor. The indirect impact would result from exploratory and production operations which are assessed in Section F.

E. SUBSEA COMPLETION SYSTEMS

The BOP unit is located on the sea bottom at or below the mudline when there is a chance for an unexpected lateral motion of a drilling platform beyond the limits allowed by the riser design. This BOP is provided with manual and automatic control shutoff provisions to insure maximum safety against well damage. The state of the art of subsea gas valves and their controls for offshore operations is well developed, and for the Arctic Sea it was initiated in the exploratory drilling by Panarctic Oils and Dome Petroleum.

The subsea production Christmas trees are employed in various seas worldwide. In the Arctic offshore application one is used in a pilot production gas well of Panarctic Oil in the Canadian Arctic Island.

There is no experience with subsea oil BOP's or trees in the Arctic Ocean although they were used successfully in other, more temperate offshore areas. The problems of contamination and sand-induced corrosion will be greater than for the gas valving and have to be considered in the design of a unit.

The main hazards to the subsea BOP's, or trees, in the Arctic Sea are grounded ice scouring the seabed, and the possibility of unit malfunctioning in the period when diver assistance cannot be provided. Permafrost is not considered a major hazard for reasons explained later.

The countermeasures consist of burial of the subsea units below the maximum scour level expected at a given location, and of improved reliability of the unit achieved either by redundancy of critical components or by improved component design. The burial can be done either by excavation of a "glory hole" or by sinking in a caisson within which the subsea unit is installed.

High reliability and diverless routine maintenance is very important for subsea units in the Arctic Ocean and a few observations on industry efforts in this area follow.

The reliability of subsea valving and control systems received industry attention. For instance, Brown and Satterwhite (1977) reviewed the inspection results of a subsea control pod which, while installed in 30m (100 ft) of water, performed satisfactorily for over a year until a boat anchor dragging across the seafloor broke a hydraulic control line. The authors were confident that improvements in the component design would further enhance subsea production control reliability.

The reliability of subsurface safety valves (SSSV) was reviewed by Purser (1977) who concluded that sandblasting was the major factor in valve wear and improvements in design were needed; that subsurface controlled SSSV's had lower failure rates than surface controlled valves; and that present USGS regulations regarding SSSV's should be amended.

The latest development in pumpdown systems, in the form of improved through-flow-line (TFL) tools, makes diverless maintenance of subsea trees a routine operation (Yonker et al, 1977). The TFL's have the ability to perform maintenance and service with flow lines up to 20 miles long, to locate down-hole equipment selectively, and to keep fluid losses to a minimum while performing service operations and other functions.

TFL technology has, however, limits to its usefulness. It cannot, for example, rectify a sticking control valve or an eroded valve seat. In such cases, a diver's assistance may be necessary.

Inherent failure-proof design, and experience with it under actual operating conditions, may be the best counter-measure.

F. LOGISTICS AND AUXILIARY FACILITIES

The transportation problems connected with offshore oil/gas operations were discussed in Section III.C. and V.E. Table 2-6 summarized the state of various transportation modes applicable to Arctic offshore. Platform-to-shore pipelines or gatherline lines were not discussed in detail except for a statement that they should be partially or totally buried to avoid the hazard of ice scour and insulated to prevent permafrost degradation, as necessary.

The main hazard to the logistics support and transportation is the environment of the Arctic, mainly the varying ice morphology, periods of poor visibility, extremely low temperatures, and sensitivity of the onshore tundra to surface disturbance.

The countermeasure would consist of adequate knowledge of the environment and its extremes, backed up by observations and predictive models; of advanced planning for modes of operation, of realistic contingency plans, and of adequate technology for implementation of such plans.

The environmental impact of transportation will depend on the selected mode of operation. The need to minimize this impact may lead to the development of some new technology such as non-propelled and self-propelled ACV's adapted for offshore and onshore operation.

Auxiliary facilities, maintenance centers, camp facilities for personnel, treatment plants, reinjection facilities, power plants, communication and control systems, and byproduct and waste disposal are state of the art. Step-by-step phasing-in of facilities in the exploration, development and production of a field was described in the Arctic Institute of North America report (1975).

The main problems connected with these facilities would be a judicious selection of sites, of adequate storage of parts and supplies, of transportation modes, of waste disposal modes, and of construction material sources which would limit environmental impact to an acceptable level and allow preservation of the way of life for natives of that area. Thus, the problems of logistics and facilities are not as much technological as they are socioeconomic and environmental.

G. PERMAFROST

From a previous discussion on permafrost (see Section I.F.4) it appears that subsea permafrost does exist in the Beaufort Sea and that it may occur relatively near the surface in nearshore waters (up to 20m (66 ft) water depth).

Permafrost may affect dredging operations, well drilling, and pipe laying. However, it is no longer considered a major obstacle due to experience obtained in all these operations during the development of the Prudhoe Bay reservoir and Alyeska pipeline. Many reports on well-casing problems, and solutions when drilling in permafrost, were published by the staff members of Atlantic Richfield, Exxon and SOHIO-BP, the operators of Prudhoe Bay, and on the pipeline by the staff of Alyeska and others. Consequently, the countermeasure is the experience and the know-how now available. Undersea permafrost may thaw more readily than onshore because of relatively high sea water temperature (minus 1.8°C) (29°F), but on the other hand it will not refreeze so readily. Knowledge of the extent and characteristics of the permafrost in a given location is required in applying existing experience so that proper design solutions can be applied.

H. WELL BLOWOUT

Well blowouts in the Arctic offshore can occur for such reasons as high formation pressures, frozen hydrates, insufficient mud weight, lost circulation, drill stem testing, lowering or rising the drill string (swabbing on trip). Some statistics on well blowouts were discussed in Section V, but we shall assume here that it is a hazard during both exploratory and production drilling.

One of the frequently used countermeasures for well blowouts is the directional drilling of a relief well which intersects the wild well below the blowout depth for pumping cement or mud to plug the well thus enabling the operator to regain control over it.

The environmental impact of an oil spill and the countermeasures to contain it were discussed in Section V.F. The discussion here will address itself specifically to the problem of a relief well platform. This is a problem peculiar to the Beaufort Sea due to its inaccessibility during certain seasons and because of the severe climatic conditions.

Apart from any effort to contain the spilled oil and to clean it up following a blowout, regaining well control to stop the pollution source should receive first priority. Arctic Institute of North America (1974) analyzed the time required to perform the necessary function of relief well drilling in the Arctic offshore, arriving at a total time before blowout was stopped of 3-1/2 to 6 months. This didn't take into account bad weather, transportation difficulties, and the allowance, for instance, of only one to nine weeks for construction of a relief drilling platform, all of which could extend this time. In another analysis, a 12-month period was estimated before a blowout in the Arctic offshore could be controlled. Whichever schedule is accepted as realistic, it is obvious that the duration of oil release could be long, if a relief is needed and all reasonable steps possible should be taken to reduce it.

One of the obvious ways of reducing the time for relief well drilling is to have a relief platform and a relief rig standing by during the drilling phase. The economic penalty for such a solution is realized. However, it was imposed by the Canadian Government and accepted by the operators of the Canadian Beaufort Sea for drilling offshore from a floating platform. This restriction did not apply to drilling from artificial islands.

In the discussion on well blowouts in Section V it was brought up that blowout of an oil well during the exploratory drilling is statistically remote and much less likely than that during a production phase. However, this report will not attempt to judge whether relief platforms should be supplied in the production phase only, but rather assumes they will be provided from the start of Beaufort offshore oil/gas activities. If a case can be made for a specific location, indicating that a relief standby platform is not needed, then the burden of such a proof should rest with the field operator.

We shall consider annual seasons and examine the type of relief platform which could be employed.

1. Winter Exploratory Drilling (December-May)

During this period, an artificial ice platform could be built for a relief well in shallow waters (small ice movement) at a distance from the main site allowing drilling within an acceptable range of directional drilling angles (probably several thousands of feet away), and in a zone of least ice movement. The standby drilling rig does not need to be placed on the ice platform but could be available from a place sheltered from major ice movement.

2. Spring (Breakup, June-July)

No easy way can be found to build a relief drilling platform during this period but a relief artificial sand/gravel island could be constructed during the preceding winter months or a nearby natural island could be used. A drill rig could be placed directly on the island when required. The alternative to these options would be to stop drilling during the breakup period.

3. Summer Period (August-September)

A drilling barge could be towed to a location, provided it was winterized nearby (example, Prudhoe Bay). The barge with a tug would then standby during the summer exploratory drilling.

4. Fall (Freeze-up, October-November)

The fall situation is similar to the spring breakup in that an artificial island for a relief well would have to be built during the summer months and a drill rig placed on it. The alternative would be to stop drilling until the ice is thick enough to permit construction of an ice pad for a relief platform.

It is obvious that any arrangement for relief structures and standby drilling equipment will increase the cost of offshore operations, but this may be unavoidable if the environment is to be preserved. Tradeoffs may have to be performed to decide on the best course of action.

Cessation of exploratory drilling during the break-up and freeze-up period would have the additional advantage of eliminating the difficult problem of oil containment and clean-up during that time, and of transportation of men and equipment.

In addition to a relief drilling platform and rig, booms surrounding a drilling platform to contain oil would provide a reasonable assurance of minimizing environmental damage caused by a well blowout.

5. Air Cushion Vehicles

An alternative option for a relief platform is the use of air cushion vehicles as drilling platforms. If the vehicle is non-propelled and has to be brought to a location, its use would be limited to the season when a marine tug or a land truck could perform the towing, i.e., summer or winter. Smaller self-propelled ACV's could also be considered for towing an ACV barge.

If the air cushion vehicle is self propelled it could very likely provide a year-round support for relief well drilling. However, before this concept is considered feasible, an appropriate size vehicle has to be built and tested under the actual conditions of the Beaufort Sea.

In the discussions above, we have referred to the relief wells needed in exploratory drilling for control of a wild well. It is however likely that such safeguards would be of more importance in the development and production phase. Kash (1973) quoted, in fact, statistics which indicated that 65 percent of blowouts occurred during production, human error and storms being the causes.

A summary of relief well platform options as a function of seasons with an estimate of time to start drilling is shown in Table 6-1. In cases where the standby drill rig is already installed on the platform, the time to start drilling is estimated at one week. When the standby drill rig is stored nearby, additional time is required for its transport and installation.

I. SAFETY STANDARDS

Safety standards resulting from the discussion of hazards and countermeasures can be divided into six groups: (1) safety standards for structure design, construction and installation; (2) safety standards applicable to operational procedures; (3) safety standards applicable to personnel; (4) safety standards applicable to emergency operations;

Table 6-1. Relief Well Platform Alternatives

TYPE OF RELIEF WELL PLATFORM	SEASON				TIME TO START DRILLING
	WINTER (Dec.-Apr.)	BREAK-UP (May-July)	SUMMER (Aug.-Sept.)	FREEZE-UP (Oct.-Nov.)	
Back-up Thickened Ice Platform	YES	N/A	N/A	N/A	3 WEEKS
Air Cushion Drilling Barge	YES	N/A	YES	N/A	1 WEEK
Marine Drilling Barge	N/A	N/A	YES	N/A	1 WEEK
Barrier Island	YES	YES (Assumes Access)	YES	YES (Assumes Access)	3 WEEKS
Back-up Artificial Sand/Gravel Island	YES	YES (Assumes Access)	YES	YES (Assumes Access)	1 WEEK
Self-Propelled Air Cushion Vehicle	YES	N/A	YES	YES	1 WEEK

(5) safety standards applicable to navigational safety of passing vessels; and (6) safety standards concerned with continued "good health" of the structure and equipment.

There are various existing regulations related to these standards and they are quoted, for instance, in API RP 2A which contains practices for the planning, design and construction of fixed offshore platforms. Consequently, only those standards that are unique for the Arctic environment of Beaufort and Chukchi Seas will be discussed here.

1. Structure Design

Safety standards for structures should include rules for safety factors of static and dynamic ice forces, ice override, and ice scouring. The ability of all materials to withstand low temperatures should be stressed and appropriate limits for fracture toughness of steels defined.

2. Operational Procedures

Operational safety standards should limit the time and conditions required for men to perform any function while exposed to the environment. These functions should be simple and foolproof. Since most of the working areas would be enclosed, gas pollution indicators should be numerous and a permanent feature of such areas. Fire prevention precautions should be stringent and scrupulously enforced.

3. Personnel

Employees should be trained physically and psychologically to perform as efficiently as possible and to be able to withstand the rigorous Arctic environment. In that respect, the experience acquired in Prudhoe Bay operations should be very valuable.

During "whiteout," and periods with a high chill factor, or when other extreme conditions specific to the Beaufort Sea exist, correct behavior should be taught and become a part of the drill procedure.

4. Emergency Operations

Emergency situations should be delineated considering the seasonal differences of the Beaufort Sea. Regular drill procedures for dealing with emergencies are recommended to maintain alert and well-trained personnel.

5. Navigational Safety for Passing Vessels

Rigid navigational safety standards should take into account periods of very low visibility.

6. Maintenance of Structural Equipment

Safety standards for inspection and maintenance should consider low water temperatures and high turbidity where underwater inspection is required. Special attention should be paid to structural members exposed to low air temperature and to the dynamic loads, so that incipient cracks could be detected.

It can be concluded from this brief discussion that the unique features of the Arctic Sea require a set of safety standards tailored to the environment. Such standards should be defined before the start of any major offshore operations.

VII. CONCLUSIONS

A. Technology for exploratory drilling in shallow waters of the Beaufort or Chukchi Seas is, in general, available. Considerable experience has been obtained by Canadian operators in the Canadian portion of the Beaufort Sea (see Section II.A, B, C) and some by the U.S. industry in the Prudhoe Bay development (14 wells drilled offshore). Some experience is presently being obtained in the shallow near-shore waters of Prudhoe Bay by U.S. operators.

B. Technology for containment of major oil spills (such as well blowout) in the Arctic offshore is not yet proven. In particular, during the period of ice break-up (May-July) and ice freeze-up (October-November), a containment of oil and logistic support could be difficult. Consideration may be given to limiting exploratory drilling in these two periods to areas where emergency access can reasonably be attained (see Section V.F, H).

C. Experience with oil spills in other areas indicated a need for a prior formulated plan for oil spill containment, cleanup and disposal adapted for regional and location specific conditions. It appears, therefore, that in addition to the existing National Contingency Plan (1968) detailed regional plans for the Beaufort Sea may be required (see Section V.F.4).

D. The technology for building relief platforms (for control of possible blowouts) in the Beaufort Sea is not yet established and studies of such platforms and the need for them would be recommended (see Section V.H).

E. There is a lack of design guidelines and practices for artificially constructed sand/gravel islands and ice islands or platforms.

F. There are gaps in the environmental data related to the Beaufort and Chukchi Seas on storm waves, storm tides, ice movement, ice override, ice scour, ice sail/keel height, and ratios. Some of these gaps are listed in Section VIII (also see Section I.F). Additional data could be obtained and incorporated in a general information center.

G. There is a lack of geotechnic data for Beaufort and Chukchi Seas on seabed soil physical characteristics, on the configuration of subsea ice-bearing and ice-bonded permafrost (see Section I.E), and on sand/gravel availability (see Section II.A). Information presently being obtained by the Department of the Interior within the proposed lease sale area should be of considerable value; however, additional information will be required on a site specific basis.

H. Statistical data on storm wave heights, wave energy spectra, ice movement and sail/keel heights and ratios in various ice zones are desirable to enable development of hindcasting mathematical models for storm waves and ice movement (see Section I.C, D, F).

I. Existing safety standards should be reviewed to consider unique features of Arction offshore. Experience available from Canadian offshore drillings and from onshore Prudhoe Bay operations would be useful in preparation of such standards (see Section VI.I).

J. Production platforms with a 20-year or more survival period in the Arctic Sea are only in the conceptual phase and would most likely require a proof of concept before their long-term use. Artificial sand/gravel islands with reinforced slopes probably offer the best chance of survival at present in water depths less than 20m (60 ft) (see Section III.A).

K. The problem areas (areas of concern) for offshore structures were discussed in Section IV, V, and VI of this report. They are summarized in Table 7-1.

Table 7-1. Problem Areas (Areas of Concern)

HAZARD	MITIGATION MEASURES	SUCCESS OF MITIGATION
Oil Spill	In open waters (summer) standard developed techniques can be used. Oil under ice - clearing techniques now under development.	Fair. In ice infested waters (spring and fall) there is at present no proven technique for clean-up.
Ice Movement	Design for ice forces. Limit drilling to 15-20m isobath for near term development.	Good, but more information on ice movement needed.
Ice Scouring	Bury wellheads and pipelines below the depth of scour.	Good, but more information on scouring depth needed.
Ice Override	Provide protection devices to break ice in flexure: provide sufficient runup and freeboard.	Good, but more information on override heights needed.
Transportation	Avoid disruption of tundra by using low surface pressure vehicles; air-surface vehicles could be used if developed.	Good. Experience in Prudhoe Bay and Alyeska pipeline should be used.
On and Offshore Dredging for Sand and Gravel	Avoid environmentally sensitive areas: beaches, barrier islands, riverbeds.	Good, but more data on stratigraphy of sand/gravel in Beaufort and Chukchi seas needed.
Subsea Permafrost	Well casings and buried pipelines should utilize Alyeska experience where appropriate.	Good, but more information on depth and characteristics of subsea permafrost needed.

Table 7-1 (cont'd). Problem Areas (Areas of Concern)

HAZARD	MITIGATION MEASURES	SUCCESS OF MITIGATION
Waste Disposal	Disposal of drilling mud, chemicals and human waste should follow OCSEAP recommendation. Prudhoe Bay experience applicable. Mud disposal on top of fast ice should be considered since it may be environmentally attractive.	Good
Personnel	Special training of personnel to operate under Arctic conditions. Operations requiring exposure to be minimized and simplified.	Good
Water Supply	Avoid draining from rivers in winter to safeguard the fish life. Construct artificial lakes.	Good

VIII. INFORMATION GAPS

The technical community should have reliable estimates of the extreme and nominal environmental conditions to design and construct safe structures in the Arctic OCS. Sufficient data on environmental stresses and phenomena should be available to develop predictive quantitative models that could be used in preparation of design criteria. In recognition of this need, the federal government and industry had initiated research programs to obtain the needed data. There now appears to be some data on ice movement, storm waves, storm surge and permafrost to develop preliminary estimates of the environmental forces. However, there is still not enough data to define these forces within narrow bands. Information is also still lacking on the potential impact of offshore oil/gas operations on the marine biota. Consequently, the designers not having sufficient information over-design their structures to compensate for the sketchy nature of the data. To optimize structural design and minimize the environmental impact, additional and more detailed environmental measurements are required. For this reason, the apparent gaps in data/information have been identified.

The following list of gaps in the state of knowledge have been gathered from analysis of OCS and POAC papers, of Alaska Oil and Gas Association (AOGA) published documentation; of the Arctic Institute of North America Reports; of

OCSEAP Synthesis Reports (1977-1978); and of Canadian sources such as the Beaufort Sea Project. It is realized that the American and Canadian oil industries have acquired more information on the Beaufort Sea environment but this information is proprietary or unavailable. The data gap assessment was based on published information only. It is possible that some of the gaps listed below are already filled by ongoing private research.

Table 8-1. Data Gaps

TYPE OF DATA NEEDED	INDUSTRY SPONSORED RESEARCH	RATIONALE
ICE		
Obtain statistical data on ice ridge characteristics and movement in the stamukhi zone.	AOGA Project Number 27, 39 Availability of Data 1981, 1982	Some data was obtained by AOGA. This data, if available, together with others existing in the public domain, should be analyzed and supplemented with more observations to enable the formulation of a predictive model.
Gather empirical data on the ice override relating it with meteorological data.	AOGA Project Number 27, 39, 42, 52, 53 Availability of Data 1981, 1982, 1983, 1984, 1984	Some data from override observations are available. Analytical and statistical analyses are required to produce the predictive models required by designers of structures.
Obtain statistical data on ice scouring (depth, frequency, spacing) and correlate with ice and sea bottom characteristics.	AOGA Project Number 48 Availability of Data 1984	Ice scouring may affect well heads, BOP's, and pipelines if they are not buried adequately. The existing data require systemization and analysis.
Standardization of ice strength data.		A variety of techniques are used for determination of ice strength and the results vary significantly. A uniform method should be developed.
Develop a real time system to monitor ice movement.		To provide continuous surveillance of ice movement for structures, vessels, etc. which may be vulnerable to ice movement.

Table 8-1 (cont'd). Data Gaps

TYPE OF DATA NEEDED	INDUSTRY SPONSORED RESEARCH	RATIONALE
ICE		
Adfreeze phenomenon		More data on the adfreeze phenomenon, its sheer, and breaking strength is required. The data should be related to structure interface, roughness, type of material, temperature, etc. This data will be utilized to calculate total ice loads of various offshore structures, and to evaluate means of reduction of adfreeze forces.
Statistical data on land-fast ice movement leading to formulation of a predictive model.	AOGA Project Number 52, 53 Availability of Data 1984, 1984	The actual movement of the ice is a major factor in determining potential loading on structures in the landfast ice zone. Since movement will be related to climatic factors, a historical data base of movement must be established, and the potentially related physical parameters including wind, temperature, tide and current determined to provide a base for a predictive model.

Table 8-1 (cont'd). Data Gaps

TYPE OF DATA NEEDED	INDUSTRY SPONSORED RESEARCH	RATIONALE
ICE		
Ice force analysis and measurements leading to formulation of ice forces on typical Arctic offshore structures.	AOGA Project Number 31 Availability of Data 1979 More data on large scale ice forces are needed.	A substantial research was done on ice force measurements but since ice strength data varied considerably, different formulas for ice forces are being used in the technical community. It is necessary to analyze the existing data, to supplement them with ice force measurements, if necessary. Model tests would consider the scale factor to be applicable to typical structures proposed for the Beaufort Sea.
Ice strength enhancement.		Techniques to increase (or reduce) ice strength by artificial means should be further explored. Higher strength ice segments could be utilized to develop controlled shear zones or failure planes around ice structures.

Table 8-1 (cont'd). Data Gaps

TYPE OF DATA NEEDED	INDUSTRY SPONSORED RESEARCH	RATIONALE
GEOTECHNIC		
Define subsea geology and determine the general locations and extent of permafrost at water depths out to 20 m in the Beaufort Sea lease area.	AOGA Project Number 19, 48 Data of general nature are available. More data required for permafrost characteristics in near shore areas.	A better understanding of subsea deposits and permafrost locations will be required to assess their effect on foundations for platforms, subsea well completions, and flow lines. This information will also be required to assess ice scour potential and develop buried pipeline design solutions. This data will be required on a regional and site-specific basis.

Table 8-1 (cont'd). Data Gaps

TYPE OF DATA NEEDED	INDUSTRY SPONSORED RESEARCH	RATIONALE
MARINE BIOTA		
Determine fish migration patterns in Beaufort Sea along planned lease zone.	OCSEAP Program Some OCSEAP data available. More needed on other fish species.	Artificial island construction and drilling operations could be located to avoid migration routes if the fish migration patterns are known.
Data are needed on the habits and migration patterns of land and sea animals.	OCSEAP Program Additional data is required on other species such as seals, algae.	The location and susceptibility of the following animals to disturbances due to petroleum spills, seismic pulsators, drilling structures and other containments resulting from hydrocarbon exploration. Polar Bears Whales, Fish and Seals Birds Algae

Table 8-1 (cont'd). Data Gaps

TYPE OF DATA NEEDED	INDUSTRY SPONSORED RESEARCH	RATIONALE
OIL SPILL		
Effect of oil spill on the environment in the offshore Alaskan Arctic.	AOGA Project Number 13, 41 Available data unknown for Project 13. Availability of Project 41, 1982	The interaction of crude oil and ice are not fully understood. More data are needed on behavior of oil under ice, of oil in ice, and on the surface of ice. Information on the role of ice movement in spreading or containing oil spills is needed. Data on effect of an oil slick on light transmission into the water and transfer of gases across the air-water interface is needed to predict effect on some life forms. Additional knowledge about the weathering and spreading of oil under Arctic conditions is required. Clean-up and disposal methods of oil spills in ice breakup conditions are unknown.

Table 8-1 (cont'd). Data Gaps

TYPE OF DATA NEEDED	INDUSTRY SPONSORED RESEARCH	RATIONALE
ENVIRONMENTAL CONTROL		
Fresh water supply.		Ground water and fresh water are in short supply, and overuse, particularly in winter, causes a shortage of available fresh water sources which may adversely affect the fish life. Potential conversion of sea ice or collected snow to various water uses may be an appropriate alternative.
The effects of drilling operations chemical waste on marine life, and marine biota has not been determined, and a study is needed to delineate the short and long term effect of these by-products.	AOGA Project Number 59, 65 Project 59 available in 1981 Project 65 unknown availability	The present method of waste disposal at Prudhoe Bay is to locate a surface dump adjacent to the drilling rig to contain the waste products. There are no selected methods for the disposal of chemical and human waste to minimize the environmental effect on the operation in the Arctic offshore. At the present no central processing facility has been developed to reuse the oil base mud and dispose of other waste. With the proposed offshore drilling operations in the Beaufort Sea and possible other areas, containment of waste fluids may become a problem and disposal into the sea may be considered as one of the alternatives. Consequently, a study to determine the short and long term effects on fish and benthic fish-food organisms should be conducted.

Table 8-1 (cont'd). Data Gaps

TYPE OF DATA NEEDED	INDUSTRY SPONSORED RESEARCH	RATIONALE
TRANSPORTATION		
Air-cushion vehicle assessment for transportation and drilling in the Arctic environment.	AOGA Project Number 60, 98 Project 60 available in 1984 Project 98 available in 1982	This mode of transportation can be utilized as a drilling platform as well as a supply vehicle also for clean-up in unstable ice condition. A significant advantage of air cushion vehicles is the ability to pass over delicate terrain like tundra without permanent damage or impairment. With the forthcoming large scale exploration in the Beaufort Sea, utilization of air-cushion vehicles should be investigated and, if necessary, engineering development of a suitable vehicle initiated.

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To avoid repetition, the following abbreviations have been used throughout these references:

BLM	Bureau of Land Management
CRREL	U.S. Army Cold Regions Research and Engineering Laboratory
IAHR	International Association of Hydraulic Research
NOAA	National Oceanic and Atmospheric Administration
OCS	Outer Continental Shelf
OCSEAP	Outer Continental Shelf Environmental Assessment Program
OTC	Offshore Technology Conference
POAC	Port and Ocean Engineering Under Arctic Conditions
USGS	U.S. Geological Survey

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